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Relationship between Strength Properties and Fiber Morphological Characteristics of *E. tereticornis* –Part-2. Regression and Artificial Neural Networks Analysis

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Abstract: ***Morphology of pulp significantly affect the paper properties and many researchers have made efforts to evaluate their relationship to control the paper properties. In continuation of the studies by the authors, relationship between the physical strength properties and morphological characteristics of E. tereticornis was evaluated. In order to develop the relationship between morphological characteristics of bleached chemical pulps, the changes in fiber morphology of E. tereticornis after beating to different levels was estimated. The handsheets prepared from the pulps beaten to different levels were tested for changes in strength properties. Multiple linear regression (MLR) & artificial neural networks (ANN) analysis were used to develop relationship of strength properties with the morphological characteristics of the pulp fibers. Studies have revealed that all four strength properties studied (tensile index, tear index, burst index and double fold) correlate significantly with the change in the morphological characteristics on beating. The results indicate that the MLR and ANN can be successfully used as tools to reveal the relationships between strength properties with fiber morphological characteristics in E. tereticornis pulp.***

Keywords: Model, Multiple linear regression, Artificial neural network, *E. tereticornis*, Morphological characteristics

1. Introduction

Multiple linear regression (MLR) and artificial neural networks (ANN) are the promising techniques that can be used to develop models of relationships between the paper strength properties and the morphological characteristics of pulp fibers [1,2]. Various research groups have also made efforts to explore the relationship between chemical and physical properties of the pulp fiber and their inherent paper making strength properties. MLR has been used to explore possibility of correlation between morphological features and the strength parameters by various researchers [3-11]. Similarly possibility of application of ANN in the paper industry has also been reported in various articles [12-18] to use neural network based model for prediction of paper properties based on factors related to the most important refining effects, such as the fiber and pulp average length, width and fines content. However there is no systematic study reported in the literature on relationship of morphological characteristics and strength properties of paper made from the most commonly used raw materials by the industry.

The paper quality evaluation group at CPPRI is actively working in the area of morphological characterization and to evaluate relationships between physical strength properties of paper and morphological characteristics of various pulp fibers used by the pulp and paper industry. In the earlier communication relationships between physical strength properties of paper and morphological characteristics of *S. officinarum* pulp fibers has been presented [19]. *E tereticornis* is the largest used raw material in India for paper manufacturing and therefore in present article the evaluation of relationship between pulp morphological characteristics and the strength properties of paper using MLR and ANN techniques is presented. In the study, the kraft-AQ bleached pulp of *E tereticornis* was beaten in a laboratory PFI mill to different beating levels for evaluation of morphological characteristics. The handsheets prepared from these pulp samples were then tested to estimate the change in various physical strength properties after beating. The data generated was used to develop appropriate models to find out relationship between *E. tereticornis* pulp morphological parameters and the strength properties of the handsheets. Development of models between paper strength properties and morphological characteristics for *E. tereticornis* pulp will be helpful for the paper industry to optimize and control the quality of paper.

2. Experimental

Materials and Methods

Freshly cut chips of *E. tereticornis* were collected from a pulp and paper mill located in Western Uttar Pradesh, India. Chips were further screened in a L&W vibrating chip classifier as per Scan cm 40: 01 method and chips retained on screen of slot size 7mm were used for pulping in the laboratory digester. The accepted chips were air-dried under atmospheric conditions and analysed for moisture content determination. The moisture content was determined by the difference in weight as received and after drying at 105± 2^0C as per Tappi T 264 "preparation of wood for chemical analysis‟.

Kraft-anthraquinone (AQ) pulping of the *E. tereticornis* chips was carried out in electrically heated laboratory rotary digester (Make-Weverk). The cooking conditions maintained were; Top temperature 160 °C, time 90 min, active alkali charge 16% (as Na_2O), liquor to raw material ratio 3.5:1 and AQ 0.1%. on o.d. weight of raw material.

Unbleached kraft-AQ pulp was bleached using $XOCEH_1H_2$ bleaching sequence, where „X‟ stands for xylanase stage, „O‟ for oxygen bleaching stage, „C‟ for chlorination, „E‟ for alkaline extraction, „H_1‟ for hypochlorite 1st stage and „H_2‟ for hypochlorite 2nd stage.

The bleached pulp of *E. tereticornis* was beaten in a PFI mill as per TAPPI T 248 sp-00 "Laboratory beating of pulp [PFI mill method]", at different beating levels. Each pulp sample was analyzed for morphological characterization using Morphi laboratory fiber analyser. The morphological characteristics evaluated were fiber length, fiber width, coarseness, kink angle, kinked fibers, curl rate in length of micro fibril, broken ends, fine elements (% in length) and % fines (% of area).

Laboratory handsheets of 60 g/m^2 were prepared on a British sheet former using TAPPI T 205cm-99 "Forming hand sheet for physical test of pulp". Handsheets were pressed, air-dried under atmospheric conditions, preconditioned at 27±2 ºC at a relative humidity of 65±2% and evaluated for various physical strength properties, such as tear index (TAPPI T 414 om-98 "Internal tearing resistance of paper [Elmendorf-type method]"), tensile index (TAPPI 494 om-01 "Tensile properties of paper and paperboard using constant rate of elongation apparatus"), burst index (TAPPI T 403 om-97 "Bursting strength of paper"), double fold (TAPPI T 423 cm-98 "Folding endurance of paper).

MLR and ANN Modeling methods

Multiple linear regression (MLR) and feed forward artificial neural networks (ANN) were used to predict the mechanical properties of handsheets made from *E. tereticornis* pulps.

Statistical software SPSS 16.0 was used for MLR analysis using the data sets depicted in Table 1 and Table 2. Physical strength properties of paper viz., tensile index, tear index, burst index and double fold were used as dependent variables and the morphological parameters of the pulp at different level of beating as independent variables. Only statistically significant linear regression equations (ANOVA, p-value ≤ 0.5%) were reported. The percentage deviation between the experimental and calculated values from the multiple regression equations for tensile index, tear index, double fold and burst index, were used to validate the most significant MLR models.

The MATLAB Neural Network Toolbox was used for the configuration of the ANN models. The data were randomly divided into three sets, training, validation and testing, for tensile index, tear index, double fold and burst index. 70% samples were used for the ANN training process for each of tensile strength and tear index, double fold and burst index, while the remaining 30% samples were equally divided for validation and testing processes. The data sets given in Table 1 and Table 2 were used for ANN modeling studies. The percentage error between the predicted values from the experimental samples for tensile index, tear index, double fold and burst index, were used as the performance criteria of the ANN models. The mean absolute error (MAE), the mean absolute percentage error (MAPE), the root mean square error (RMSE), and correlation coefficient (R^2) were used to evaluate the prediction performance of the models [11]. The models yielding the best results for tensile index tear index, burst index and double fold were considered as the prediction models.

One layer feed-forward network with sigmoid hidden neurons and linear output neurons were used as the activation functions to fit multi-dimensional mapping problems. The transfer function used for one layer feed forward network was "PURELIN". This was helpful to compare the one layer ANN results using PURELIN transfer function with the Multiple Linear Regression analysis. The Levenberg-Marquardt back propagation algorithm was chosen as the training algorithm in all cases.

3. Results & Discussion

Multiple Linear Regression (MLR) Analysis between Strength Properties and Morphological Characteristics of *E. tereticornis*

Strength properties of paper like tensile strength are affected mainly by the way in which individual fibers are bonded together in paper sheet. The degree of fiber bonding depends largely on the flexibility and compressibility of individual fibers [20]. The collapsing of fibers leads to the formation of paper having high tensile strength, compression strength, burst strength, tensile stiffness and elasticity. Collapsed fibers are more flexible and have a higher surface area available for bonding. However the treatment of fibers resulting in curl and sharp change in axial direction of fibers leads to lower the tensile strength. The curly fibers tend to form paper with low elastic modulus but higher stretch than paper made from straight fibers. Changes in the axial direction of fibers such as kinks, angular folds and twist are also reported to result in lower tensile strength and elastic modulus of paper [21, 22, 23].

The MLR analysis of relationship was carried out between various physical strength properties, like tear index, tensile index, burst index and double fold (Table 1) and the change in morphological characteristics of the fibers of *E. tereticornis* after different beating levels (Table 2).

Table 1: The measured values of strength parameters for E. tereticornis pulp handsheets at different beating levels

CSF, mL	*Tensile index, Nm/g*	*Tear index, mNm^2/g*	*Burst index, $kPam^2/g$*	*Double fold, number*
599	27.62±1.17	3.36±0.27	1.13±0.19	13±0.21
562	33.41±1.23	3.97±0.49	1.84±0.18	14±0.24
510	37.62±1.34	4.43±0.38	2.31±0.22	16±0.27
488	46.82±1.43	5.17±0.67	3.07±0.20	18±0.29
467	53.37±1.56	6.38±0.24	3.79±0.29	21±0.32
436	55.19±1.14	6.55±0.52	3.87±0.17	25±0.46
391	59.13±1.29	6.84±0.47	3.93±0.41	29±0.54
363	62.89±1.19	7.32±0.68	4.14±0.27	33±0.78
338	64.61±1.59	7.29±0.61	4.45±0.29	38±0.89
303	65.57±1.61	6.94±0.58	4.61±0.18	39±1.31
285	67.15±1.43	6.75±0.54	4.78±0.21	42±1.46
260	68.57±1.29	6.51±0.46	4.83±0.29	43±1.21
242	69.16±1.54	6.36±0.59	4.88±0.23	44±0.93

± refers standard deviation

Table 2: *Morphological characteristics of E. tereticornis pulp fibers at different beating levels*

CSF, mL	Weighted fiber length, mm	Fiber width, µm	Coarseness, mg/m	Kink angle, degree	Kinked Fibers, %
599	0.791	18.4	0.0569	123	46.5
562	0.782	18.5	0.0565	122	45.2
510	0.774	18.7	0.0563	122	43.8
488	0.767	18.8	0.0561	121	41.2
467	0.761	18.9	0.0558	122	40.9
436	0.758	18.9	0.0541	123	39.8
391	0.756	18.9	0.0532	124	39.1
363	0.752	19.0	0.0523	125	38.8
338	0.748	19.0	0.0518	126	38.3
303	0.736	19.0	0.0494	127	36.2
285	0.720	19.1	0.0489	130	35.4
260	0.718	19.1	0.0484	133	34.3
242	0.716	19.1	0.0478	135	32.2

Table 2: *Contd….*

CSF, mL	Curl, %	Percentage in length of Macro fibrils, %	Broken Ends, %	Fine elements, % in length	Fine elements, % in area
599	12.5	0.533	17.29	28.8	9.36
562	11.8	0.547	17.51	30.9	10.01
510	11.1	0.552	17.90	32.1	10.58
488	10.8	0.568	18.78	34.2	11.14
467	10.2	0.589	18.55	36.7	11.77
436	10.1	0.594	18.63	37.1	11.91
391	9.9	0.598	18.72	37.4	12.28
363	9.7	0.601	18.94	37.9	12.45
338	9.5	0.605	19.12	38.8	12.53
303	9.2	0.612	19.45	39.1	12.88
285	9.0	0.619	19.87	39.5	13.07
260	8.7	0.647	19.97	39.9	13.11
242	8.5	0.673	20.10	40.2	13.17

The results of MLR analysis showing correlation of the significant morphological parameters with physical strength properties are presented in Table -3.

Table 3: MLR analysis of relationship between tensile index, tear index, burst index and double fold numbers and significant morphological characteristics of E. tereticornis pulp fibers.

Dependent Variable	*Predictors*	*Coefficient*	*Sig.**	*Ind. R^2**	*Mult. R^2**
Tensile index, Nm/g	Constant	-191.393	.000	-	0.998
	CSF, mL (X_1)	-0.113	.001	0.965	
	Coarseness, mg/m (X_4)	1117.657	.028	0.890	
	Curl, % (X_7)	8.557	.002	0.983	
	Fine elements (%) in length, (X_{10})	4.025	.000	0.995	
Regression model: Tensile index (Nm/g) = $-0.113X_1+1117.657X_4+8.557X_7+4.025X_{10}-191.393$					
Tear Index, mNm2/g	Constant	-49.758	.000	-	0.970
	Fiber length, mm (X_2)	45.112	.000	0.724	
	Fine elements (%) in length (X_{10})	-0.600	.000	0.931	
Regression model: Tear index (mNm2/g) = $45.112\ X_2+0.600\ X_{10}-49.758$					
Burst index, kPam2/g	Constant	-23.708	.0002	-	0.998
	Fiber width,μm (X_3)	0.921	.000	0.999	
	Fine elements,% in length (X_{10})	0.274	.025	0.989	
Regression model: Burst index (kPa.m^2/g) = $0.921\ X_3+0.274\ X_{10}-23.708$.					
Double fold, number	Constant	-44.123	.239	-	0.995
	CSF, mL (X_1)	-0.187	.000	0.988	
	Curl, % (X_7)	11.313	.001	0.948	
	Fine elements,%in length (X_{10})	3.283	.005	0.924	
	Fine elements,% in area (X_{11})	-7.145	.046	0.942	
Regression model: Double Fold (Number) = $-0.187\ X_1+11.313\ X_7+3.283\ X_{10}-7.145\ X_{11}-44.123$.					

*significance, Individual R^2, Multiple R^2

Results of stepwise MLR analysis presented in Table-3 reveal that the tensile strength of hand sheets made from *E. tereticornis* is significantly affected by CSF, Coarseness, Curl and Fine elements percentage in length. The most dominating independent variables affecting tensile strength were CSF, curl, fine elements (%) in length which accounted for 96.5% and 98.3% and 99.5% variation in tensile index respectively. Coarseness accounted for 89.0% of the variations. The multiple regression analysis involving these variables accounted for 99.8% of the total variation.

Tear index is the function of fiber length [24]. Greater the fiber length, higher will be the tearing resistance of paper [20, 25]. Fibril angle is the other factor that has the significant influence on stretch properties (extensibility) of a sheet. Multiple linear regression analysis revealed that interaction of fiber length and fibril angle could account for 76% of the variation in tearing strength for unbeaten hardwood pulp [20]. The curly fibers are reported to lead to high tear index due to uneven distribution of stresses along the length of a curled fiber in a fracture-zone [26,27]. Other investigator has reported that an increase in the number of dislocations in fibers causes an increase in tear strength and stretch but decreases bonding strength [28].

Beating of fibers also affects tear as at low level of beating, fibers are pulled out intact due to weak inter fiber bonds compared to the strength of the fibers as the fracture propagates across the sample. At higher levels of beating the inter fiber bond strength is higher and therefore fibers start to break instead of being pulled out intact.

MLR of tear index with morphological characteristics reveals that the major affecting factors are Fiber length and Fine elements in length. The more dominating among of these two variables is fine elements (% in length) which accounted for 93.1%, whereas the fiber length accounted for 72.4 % of the variations.

Effect of morphological characteristics on burst strength has been studied by many researchers. It is reported to be dependent on lumen width, fiber diameter, specific gravity, Runkel ratio, percentage of fines, coarseness etc.[20, 29,30]. Bursting strength is affected mainly by the way in which individual fibers are bonded together in paper sheet.
MLR analysis between burst index and morphological characteristics of *E. tereticornis* pulp fibers revealed that the dominating factors were fiber width and fine elements (%) in length. Fiber length and fine elements accounted for 99.9% and 98.9% variations in the burst index respectively.

The double fold number of paper has been reported to be dependent on various morphological characteristics of pulp fibers; like thick/thin walls of fibers, Runkel ratio, fiber coarseness etc [25, 29, 30]. The most significant MLR model shown in Table 3 revealed that the dominating factors affecting double fold were CSF, Curl, Fine elements in length and Fine elements in area. CSF, Curl, fine elements (% in length) and fine elements (% in area) accounted for 98.8%, 94.8 %, 92.4% and 94.2% variation in double fold respectively. The significance levels for tensile index, tear index, burst index and double fold were found to be less than 0.05 in all the MLR models shown in Table 3. .

The regression models of relationship between tensile index, tear index, burst index & double fold (dependent variables) and various morphological characteristics (independent variables) were validated using experimental data limits. The percent deviation between experimental and the calculated values of tensile index, tear index, burst index and double fold number were found to be within the acceptable limits. (Figures 1 – 4)

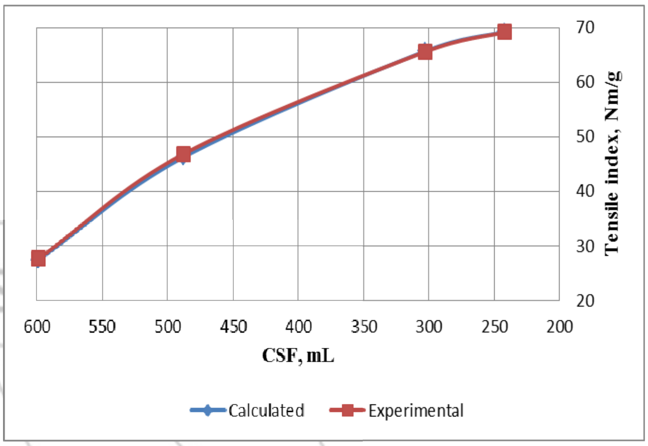

Figure 1: Relationship between calculated and experimental values for tensile index of E. tereticornis handsheets using MLR model equations

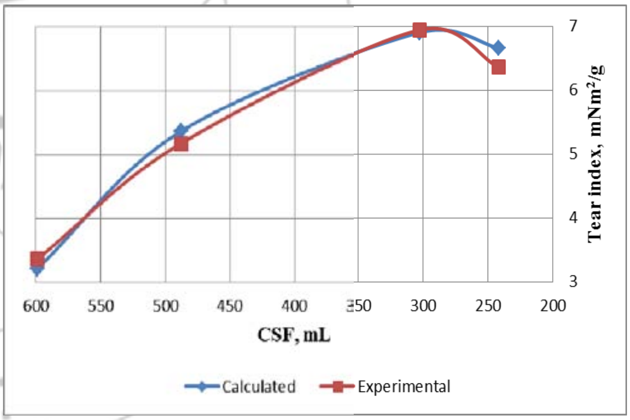

Figure 2: Relationship between calculated and experimental values for tear index of E. tereticornis handsheets using MLR model equations

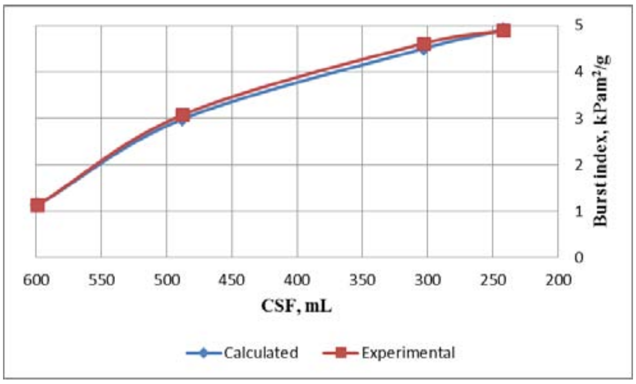

Figure 3: Relationship between calculated and experimental values for burst index of E. tereticornis handsheets using MLR model equations

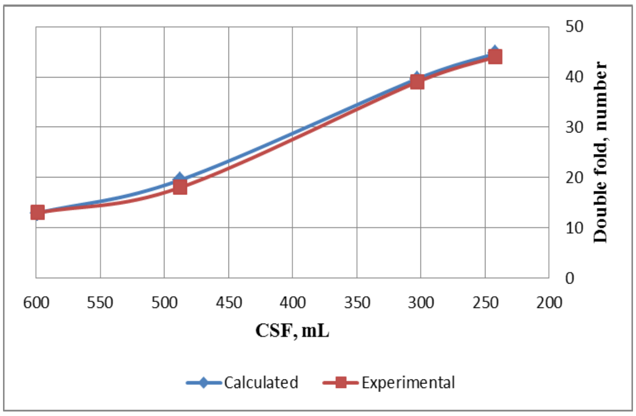

Figure 4: Relationship between calculated and experimental values for double fold of E. tereticornis handsheets using MLR model equations

Artificial Neural Network analysis of Strength Properties and Morphological Characteristics of *E. tereticornis.*

The one layer feed-forward network models with sigmoid hidden neurons and linear output neurons were used to compare the ANN results with the MLR analysis of strength properties with morphological characteristics of *E. tereticornis* pulp fibers beaten for different beating levels. The transfer function used for one layer feed forward network was “PURELIN”.

The morphological characteristics of *E. tereticornis* pulps, beaten to different freeness levels (Table 2) were used for the ANN testing, training and validation process for hand sheet strength parameters, as input variables. The output variables in the models were the measured values of tensile index, tear index, double fold and burst index for different pulp freeness levels of pulps (Table 1).

The percentage error between the predicted values from the experimental samples for tensile index, tear index, double fold and burst index was used as the performance criteria of the ANN models. The predicted values and percentage errors observed in tensile index tear index, double fold and burst index for hand sheets made from *E. tereticornis* pulps are shown in Table 4.

Table 4: Predicted values and percentage errors of strength properties of E. tereticornis handsheets using one layer linear ANN networks

CSF (mL)	Tensile Index		Tear Index		Burst Index		Double fold	
	P	E	P	E	P	E	P	E
599	27.6	-2.1 E-14	3.4	-7.8 E-10	1.13	-3.9 E-08	13	0
562	33.4	0.00	4.0	-3.9 E-10	1.84	-4.8 E-08	14	4.0 E-07
510	37.6	-0.00	4.4	7.4 E-10	2.31	-1 E-08	16	2.6 E-07
488	46.8	0.00	5.2	1.9 E-09	3.07	6.5 E-09	18	6.6 E-07
467	53.4	0.00	6.4	1.8 E-09	3.79	1.3 E-08	21	1.4 E-06
436	55.2	0.00	6.5	1.6 E-09	3.87	1.6 E-08	25	8.8 E-07
391	59.1	0.00	6.8	3.4 E-06	3.99	-0.06	29	1.0 E-06
363	62.9	0.00	7.3	4.3 E-10	4.14	4.6 E-08	33	7.7 E-07
338	64.6	0.00	7.3	1.5 E-09	4.45	7.3 E-08	38	5.6 E-07
303	65.6	0.0	6.9	1.9 E-09	4.61	1.6 E-07	39	1.8 E-07
285	67.1	0.01	6.7	2.0 E-09	4.78	2.1 E-07	42	1.1 E-07
260	68.6	-0.1	6.5	2.2 E-09	4.83	2.4 E-07	43	-3.7 E-06
242	69.0	0.1	6.4	0	4.88	2.6 E-07	44	0.0

Table 4 . contd…..

*P and E denote predicted values and error in % respectively

Results show that while comparing predicted values to measured values, in most of the cases the neural network prediction is very close to the measured values.
Performance criteria values used to assess the performance of the proposed prediction models are given in Table 5. The prediction values were clearly determined with very low percentage errors. The low level of errors is satisfactory for predicting the strength properties of the hand sheets. This also demonstrates that the networks effectively give accurate results.

Table 5: Performance criteria used for predicting various strength properties of E. tereticornis hand sheets using one layer linear ANN networks

Performance criteria	Tensile Index			Tear Index		
	1*	2*	3*	1*	2*	3*
MAE	0.003	0.003	0.018	0.000	0.000	0.000
MAPE	0.000	0.001	0.005	0.000	0.000	0.000
RMSE	0.015	0.008	0.045	0.000	0.000	0.000
R2	1.000	1.000	1.000	1.000	1.000	1.000

*1= Training, 2= validation, 3= Testing

Performance criteria	Burst Index			Double fold		
	1*	2*	3*	1*	2*	3*
MAE	-0.002	-0.01	-0.01	0.000	0.000	0.000
MAPE	-0.002	-0.05	-0.04	0.000	0.000	0.000
RMSE	0.012	0.024	0.024	0.000	0.000	0.000
R2	1.000	1.000	1.000	1.000	1.000	1.000

*1= Training, 2= validation, 3= Testing

Regression analysis between the predicted values and the measured values is generally used to assess the validity of the networks and their accuracy. Figures 5 to 8 show the relationship between the measured values and predicted values for training data, validation data, testing data and all data in predicting tensile index, tear index, double fold and burst index, respectively.

In Figures 5- 8, the predicted values are plotted against the measured values as open circles. The best linear relationship is shown with a dashed line. In addition, the perfect linear relationship between measured values and the predicted values in predicting tensile index and burst index is indicated by a solid line.

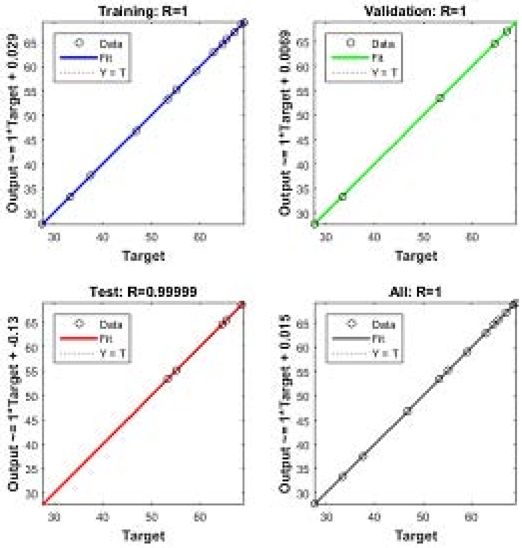

Figure 5: Relationship between measured results and predicted results for tensile index of E. tereticornis handsheets using one layer linear ANN networks.

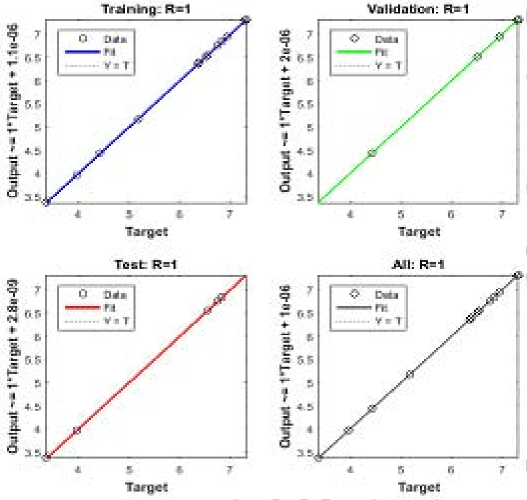

Figure 6: Relationship between measured results and predicted results for Tear Index of E. tereticornis handsheets using one layer linear ANN networks.

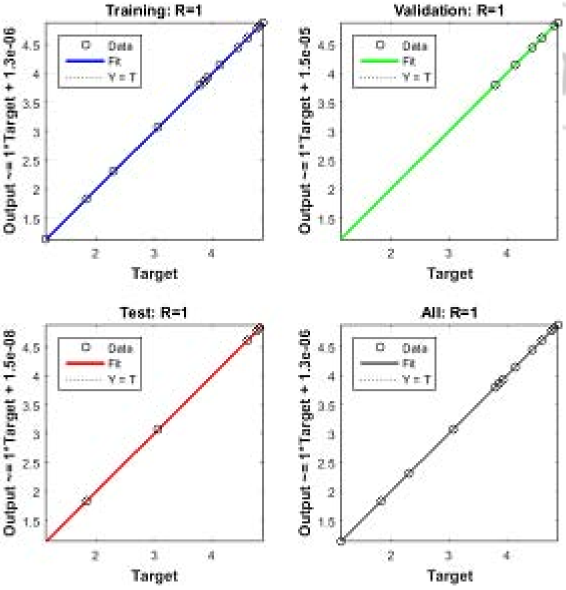

Figure 7: Relationship between measured results and predicted results for Burst Index of E. tereticornis handsheets using one layer linear ANN networks.

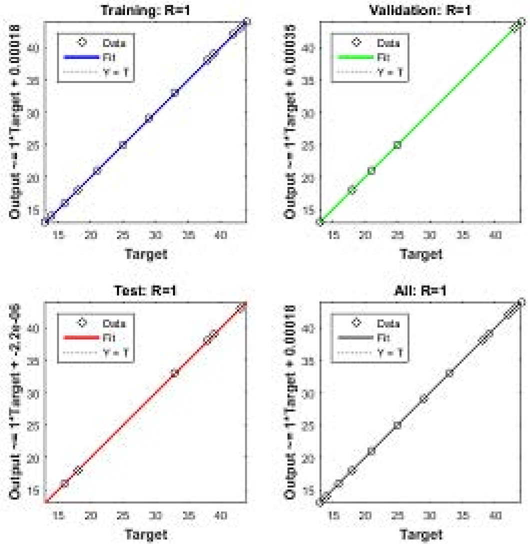

Figure 8: Relationship between measured results and predicted results for Double fold number of E. tereticornis hand sheets using one layer linear ANN networks

The accuracy of the prediction models for tensile index of handsheets made out of *E. tereticornis* pulp is proved by the increasing correlation coefficient (R^2) values. As R^2 approaches 1, prediction accuracy increases. Analysis of the measured and predictive results of tensile index, tear index, burst index and double fold for *E. tereticornis* handsheets using one layer ANN network with linear transfer function reveals that the predicted values are very close to the measured values for all parameters. However in case of *S. officinarum*, the relationship of morphological characteristics was not observed with tear index and double fold. The results are presented in the first part of this publication published elsewhere [19].

The ANN results strengthen the reliability of the ANN models as they successfully predict correlation of the strength properties with morphological parameters of *E. tereticornis* pulp handsheets without time consuming and costly comprehensive experimental investigations. The ANN results also compliment the MLR analysis results for tensile index, tear index, burst index and double fold in case of the *E. tereticornis* pulp handsheets.

4. Conclusion

The predicted results of relationship between physical strength properties viz., tensile index, tear index, burst index & double fold with morphological characteristics of pulp using MLR and ANN analysis were found to be highly satisfactory in terms of explanatory characteristics and validity of the models for *E. tereticornis* pulp handsheets. The results indicated that the MLR and ANN approaches can be successfully used to model the effects of *E. tereticornis* pulp beating level with strength parameters.

The MLR and ANN models can be used to design tailor-made products meeting specific requirements by altering the morphological characteristics of the pulp fibers by the paper industry.

References

[1] W. Ingmanson , E. Thode. “Factors contributing to the strength of a sheet of paper”. Tappi J, 42, 1: 83, 1959.

[2] D.H. Page, “A theory for the tensile strength of paper”, Tappi J, 52, 4: 674, 1969.

[3] D.H. Page, “The mechanism of strength development of dried pulps by beating” SvenskPapperstidn, 88, 3, R30, 1985.

[4] H.W. Emerton, “Fundamentals of the Beating Process: The Theory of the Development in Pulps of Papermaking Characteristics by Mechanical Treatment”, British Paper and Board Industry Research Association, Kenley, UK, 1957.

[5] J. d‟A. Clark. “Some thoughts on fiber classification and length”. Tappi J, 68, 8: pp. 119, 1985.

[6] L. Paavilainen, “Importance of particle size, fibre length and fines for the characterization of softwood kraft pulp”, PaperiJaPuu, 72, 5: pp. 516, 1990.

[7] K. Olejnik. “The Effect of Specific Refining Intensity on Paper Breaking Length”, Paper Technology, 52, 2: pp. 8-11, 2011.

[8] M.S. Jahan, S. Rawshan, “Reinforcing potential of Jute pulp with TREMA ORI-ENTALIS (NALITA) pulp”. BioResources, 4, 3: pp. 921-932, 2009.

[9] O. Chagaev, X. Zou, “A New Concept to Characterize Fibre Development in Refining and Mechanical Pulp Quality for LWC and SC Grades”, Pulp Pap. Canada, 108, 1: pp. 50-56, 2007.

[10] J. Risen, A.H. Hulten, M. Paulsson, “Influence of fiber properties on the network strength of softwood and hardwood kraft pulp fibers from different stages of a bleaching sequence.” Journal of wood and Technology, 24(4): pp. 289-306, 2004.

[11] R.C. Neagu, E.K. Gamstedt, F. Berethold, “Stiffness contribution of various wood fibers to composite materials.”Journal of composite material, 40(8): pp. 663 – 699, 2006.

[12] N. Gurnagul, D.H. Page, M.G. Paice, “The effect of cellulose degradation on strength of wood pulp fibers,” Nordic Pulp & Paper Research Journal, 7(3) : pp. 152-154, 1992.

[13] O. Joutsimo, R. Wathén, T. Tamminen, “Effects of fiber deformations on pulp sheet properties and fiber strength” Paperi ja Puu – Paper and Timber, 87(6): pp. 392-397, 2005.

[14] F.F. Wangaard, G.E. Woodson, “Fiber Length and Fiber Strength Interrelationship for Slash Pine and its effect on Pulp Sheet Properties”. Wood Science 5(3): pp. 235 – 240, 1973.

[15] M.G. Carvalho, P.J. Ferreira, M.M. Figueiredo, “Cellulose depolymerisation and paper properties in E. globulus kraft pulps”. Cellulose 7: pp. 359–368, 2001.

[16] A. Oluwadare, A. Oluwafemi, O.S. Ashimiyu, Sotannde Middle-East Journal of Scientific Research 2 (2): pp. 63-68, 2007.

[17] H. Pereira, A. José, A. Santos, O. Anjos, “Fiber Morphological Characteristics of Kraft Pulps of Acacia melanoxylon Estimated by NIR-PLS-R Models”, Materials, 9, 8, 2016.

[18] H.C. Kim, X. Shen, M. Rao, J. Zurcher, “Quality prediction by neural network for pulp and paper processes”. In: Canadian Conference on Electrical and Computer Engineering. Vancouver, BC, ISBN:0-7803-2416-1, 1: pp. 104-107, 1993.

[19] M. Gyaneshwar, D. Hart, W.E. Scott, “Development of Mathematical Models for Predicting Sizing, Strength, and Opacity on the Miami University Pilot Paper Machine”, In: 2000 TAPPI Papermakers Conference, Atlanta, GA : TAPPI Press, 2000.

[20] B.S. Dayal, J. MacGregor, P.A. Taylor, “Application of Feedforward Neural networks and Partial Least Squares Regression to Modeling Kappa Number in a Continuous Kamyr Digester”, Pulp and Paper Canada, 95: pp. 26-32, 1994.

[21] J. Zhu, Q. Xia, M. Rao, J.A. Zurcher, “Neural Network for Modeling Pulp Process”, Pulp and Paper Canada, 98, 9: pp. 35-38,1996.

[22] K. Olejnik, K. Ciesielski, “Neural network model of pulp refining process”, Chemical and Process Engineering, 25, 3-2: pp. 1411-1416, 2004.

[23] J. Scharcanski, CTJ Dodson, “Neural network model for paper forming process” In: Pulp and Paper Industry Technical Conference. 10-14, pp. 236– 255, June, 1996.

[24] K. Ciesielski, K. Olejnik, “Application of Neural Networks for Estimation of Paper Properties Based on Refined Pulp Properties”, Fibers & Textiles in Eastern Europe, Vol. 22, 5(107), 2014.

[25] P. Nieminen, T. Kärkkäinen ,K. Luostarinen, J. Muhonen. “Neural Prediction of Product Quality Based on Pilot Paper Machine Process Measurements”, ICANNGA‟11 - 10th International Conference on Adaptive and Natural Computing Algorithms; Part I: pp. 240-249, 2011.

[26] P.J. Edwards, A.F. Murray, G. Papadopoulos, A.R. Wallace, J. Barnard, “The application of neural networks to the paper-making industry”, ESANN'1999 proceedings - European Symposium on Artificial Neural Networks Bruges (Belgium), 21-23 April, 1999, pp. 69-74, 1999.

[27] G. Cybenko, "Approximation by superpositions of a sigmoidal function." Mathematics of control, signals and systems 2(4): pp. 303-314, 1989.

[28] W. Lou, S. Nakai, "Application of artificial neural networks for predicting the thermal inactivation of bacteria: a combined effect of temperature, pH and water activity." Food Research International 34(7): pp. 573-579, 2001.

[29] Jean-Luc Wertz, Bedue Oliver, P. Mercier Jean, “Swelling and Dissolution of Cellulose, Chapter 4.3: Intracrystalline Swelling”, In: Cellulose Science and Technology: pp.161, 2010

[30] A. Canakci, S. Ozsahin, T. Varol, “Modeling the influence of a process control agent on the properties of metal matrix composite powders using artificial neural networks”. Powder Technology, 228: pp. 26-35, 2012.

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