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ORIGINAL PAPER

Applying Fuzzy Logic Model for Static Puncture Evaluation of Nonwoven Needle-Punched Polyester Fabrics

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***Abstract*- Nonwoven needle-punched fabrics are the most common textile structures used as geotextiles. In most applications, geotextiles are subjected to compressive forces. These forces cause the layers to deform and eventually create puncture. The present study develops an intelligent model for the evaluation of static puncture resistance and real elongation of nonwoven needle-punched polyester fabrics using fuzzy logic method. The fuzzy logic expert system, contrary to many other mathematical methods, can considerably forecast the behavior of nonlinear complex phenomena. Parameters of needle penetration depth, needle punch density, and fabric areal weight were considered as input variables of the designed model. The experimental results were conducted by a universal strength tester based on the well-known static puncture (CBR) test method. The fuzzy model showed that puncture resistance increases with the enhancement of fabric areal weight, but excessive increase of the needling parameters causes the puncture resistance to decrease. Furthermore, the results of the model demonstrated that the fabric puncture real elongation decreases, while the input variables increase. It was also observed that the real and predicted values of puncture resistance and puncture real elongation of the fabrics were in good agreement with very low absolute error.**

***Keywords*: fuzzy logic, needle-punched fabric, nonwoven, puncture resistance, real elongation**

I. INTRODUCTION

Nonwoven fabrics are products of entangled fibrous-assembly that, due to their unique structural properties, economical aspects, and properties of the wide range of raw materials such as polyester, polypropylene, etc., can show acceptable performance in various applications of human life. It is evident that the majority of the polyester nonwoven products such as geotextiles and home/official furnishings often meet compression loading either in the manufacturing process or in their applications.

Compression loadings are forces that can lead to specific deformations of rupture. Static puncture resistance (CBR test), as a part of compression loading, is defined as maximum contact stress exerted to the fabric due to the perpendicular quasi-static movement of a plunger-shaped body.

Previous researches totally show that the areal weight, needle penetration depth, and punch density are the most significant factors affecting the structure and properties of the nonwoven needle-punched fabrics [1-8]. Debnath and Madhusoothanan [1] studied the compression behavior of polypropylene needle punched nonwoven fabrics under wet conditions. They showed that with increasing needling density, the initial thickness, percentage compression, and percentage thickness loss of the fabrics under wet conditions decrease to a higher extent compared to dry conditions. Çinçik and Erdem Koç [2] analyzed the effect of blend ratio and process parameters on the tensile properties of polyester/viscose blended needle-punched nonwovens. They concluded that the tensile strength of the needle-punched nonwovens decreases with the increase of polyester proportion in the mixture and increases with the increase in mass per unit area and punching density. In the study conducted by Kuo *et al.* [4], it was observed that significant factors that may influence the quality characteristics of needle punching nonwoven fabrics are penetration depth and needling density. Miao *et al.* [6]

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investigated the influence of needling density and depth of needle penetration on the fiber damage. They showed that with the increase in needling density and needle penetration depth, fiber breakage increases.

There are several research studies investigating the puncture resistance of geotextile fabrics. Saberi *et al.* [9] simulated the puncture behavior of nonwoven fabrics based on the hyper-elastic model, using finite element method (FEM) and considering the geotextile layer as a continuous surface. They showed that nonwoven fabrics with higher weight exhibited higher puncture stress. Mashroteh *et al.* [10] investigated puncture resistance and the relevant real elongation of the nonwoven needle-punched polyester fabrics using compressive behavior study and statistical design of the experiment. They found that fabric areal weight, needle penetration depth, and needle punch density are significantly effective on the puncture properties. Various studies of puncture resistance have also been reported for composite nonwoven fabrics. Researchers showed different behaviors of puncture resistance characteristics in nonwoven/woven fabrics compounded by Kevlar, low-T_m/high-T_m polyester, PA6 materials, etc. [11-13]. Askari *et al.* [14] in their investigation regarding the effect of fabric unit weight and penetration speed on the CBR's puncture behavior of nonwoven needle-punched polyester geotextile fabrics showed while fabric puncture resistance and relative energy are merely affected by penetration speed, fabric weight clearly influences puncture resistance, deflection, and energy. Rawal *et al.* [3] found that the area density of nonwoven needle-punched polypropylene fabrics has a significant influence on its puncture resistance; whereas, the effect of needle penetration depth is insignificant. They also observed that the effect of punch density on puncture resistance is more significant in comparison to that of needle penetration depth. Termonia introduced a geometrical model to investigate the behavior of needle-puncture resistance of plain woven fabric [15]. The results showed that the frictional parameters of the fabric play a main role in the endured puncture resistance. Ghosh [16] studied the puncture resistance of woven and nonwoven geotextile fabrics under uniform radial pre-strain. He observed lower failure strain in puncture when the test sample was pre-strained.

Published reports from a large number of puncture studies show that presenting a model with respect to the real nonlinear complexities between the input and output data of the behavior poses a major challenge for researchers, due to imprecise control of the process parameters, variety of raw materials used and so on [3,9,10,17-19]. Therefore, a fuzzy logic expert system can be employed to minimize amounts of errors forecasting a behavior with offering considerable flexibility in the evaluations [20,21].

Some predictive models based on the fuzzy logic method have been applied to evaluate fiber properties [22], a relationship between fiber and yarn characteristics [19], yarn hairiness [23], woven fabric properties [24], knitting fabric properties [25,26], a color strength of fabrics [17,18] and also the resilience of hand-knotted carpets [27].

Analytical modeling of puncture behavior of the nonwoven needle-punched fabrics, according to the fuzzy theory, has not been ever reported. The purpose of this study is to use a fuzzy inference system to model the relationship between different combinations of the variables of fabric areal weight, needle penetration depth, and punch density with puncture resistance and real elongation of nonwoven needle-punched polyester fabrics.

II. FUZZY LOGIC

Fuzzy logic was presented by Lotfi Zadeh in 1965. It is a mathematical tool that can be used for dealing with uncertainty. Fuzzy logic begins with the concept of a fuzzy set. A fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. Fuzzy inference system consists of a fuzzification interface, a database, a rule base, a decision-making unit, and finally a defuzzification interface. A fuzzy inference system is shown in Fig. 1 [28].

One of the important concepts in fuzzy logic theory is fuzzification. In the fuzzification process, the crisp quantities are converted to fuzzy (crisp to fuzzy). The conversion of fuzzy values is represented by membership functions. The membership function is a curve that converts the numerical value of an input variable into a linguistic fuzzy set within a range from 0 to 1. Among various forms of membership functions, the triangle membership function is the simplest and most often used due to accuracy which is defined as Eq. (1) [28]:

$$\mu_A(x) = \begin{cases} \dfrac{x-L}{m-L}; & L \le x \le m \\ \dfrac{R-x}{R-m}; & m \le x \le R \\ 0; \text{otherwise} \end{cases} \tag{1}$$

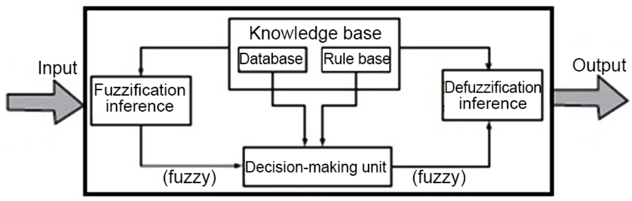

Fig. 1. Fuzzy inference system.

Where, m is the most promising value, L and R are the left and right spread (the smallest and largest value that x can take).

The knowledge base consists of a database and a rule base. In the fuzzy knowledge base system, knowledge is represented by the IF-THEN rule. Moreover, fuzzy rules are the heart of a fuzzy expert system which determines the relationship between input-output of a model. A fuzzy rule base (FRB) is constituted by the collection of IF-THEN rules. FRB can be divided into two classes, namely Mamdani and Sugeno. In the Mamdani models, both of the antecedent and consequence are in fuzzy set form, but in the Sugeno model, the antecedent is in the form of a fuzzy set and the consequence is made up by a linear equation.

Decision-making logic plays a central role in a fuzzy logic model due to its ability to create human decision-making. It deduces fuzzy control actions according to the information provided by the fuzzification module and by applying knowledge about how best to control the process. Most commonly, a Mamdani max-min fuzzy inference mechanism is used because it assures a linear interpolation of the output between the rules.

Defuzzification means the fuzzy to crisp conversions. The generated fuzzy results cannot be used in this way for applications; hence it is necessary to convert the fuzzy quantities into crisp quantities for further processing. This can be achieved by using the defuzzification process [28]. Among various methods of defuzzification, the center of gravity method is most commonly used [17,29] based on Eq. (2) [28]:

$$z = \frac{\sum_{i=1}^{n} (\mu_i - b_i)}{\sum_{i=1}^{n} \mu_i} \quad (2)$$

Where, z is the non-fuzzy numeric value, b_i is the position of the singleton in the ith universe, and μ_i is equal to the firing strength of truth values of rule i.

III. MATERIALS AND METHODS

A. Materials

To produce needle-punched nonwoven fabrics, 100% polyester fibers with an average linear density of 11 dtex and 92 mm average length (which are commonly used in industrial applications such as automotive floor-covering and geotextile) were processed on a conventional carding machine. The carded web with an average areal weight of 25 g/m^2 was fed to a horizontal cross folding unit. The folded batt was fed to a pair of needle looms, needling from top and bottom, respectively. Both looms were equipped with Groz-Beckert barbed needles coded as 15*18*32*3 R333 G1002. According to the considered levels of the input variables, seventy-five samples with different process parameters namely fabric areal weight, needle penetration depth, and punch density were prepared.

B. Test Procedure

The needle-punched nonwoven fabrics were static puncture tested by a Shirley universal strength tester based on ISO 12236 (2006) standard test method. A stainless steel plunger with a diameter of 50 mm was fixed to the load cell which showed a constant rate of movement at 50 mm/min. The tested samples were sized as 210×210 mm^2 and placed between two circular plates with a 150 mm diameter hole in the center.

The deflection value measured by the strength tester is in fact, vertical deformation of the fabric while testing; whereas, the fabric elongation is extension occurred at the fabric surface plane. Since the elongation parameter indicates how the fibers displace during the loading process, it is considered as an influential factor in studying the mechanical behavior of various fabrics in general and the nonwoven fabrics in particular. It is clear that the real elongation magnitude of the tested fabric during puncture loading can be easily calculated from the theoretical deformation geometry as shown in Fig. 2. Eq. (3) indicates the real elongation percentage of puncture (PRE) at break [10]:

$$\mathrm{PRE} = \frac{\left(2\sqrt{(R_P - r_P)^2 + h_P^2} + 2r_P\right) - 2R_P}{2R_P} \times 100 \quad (3)$$

Where, r_P is radius of the plunger device (25 mm), R_P is radius of the sample (75 mm), and h_P is deflection value (measured by the strength tester).

C. Development of Fuzzy Prediction Model

In this study, three parameters namely fabric areal weight, needle penetration depth and, punch density were used as input and puncture resistance and puncture real elongation

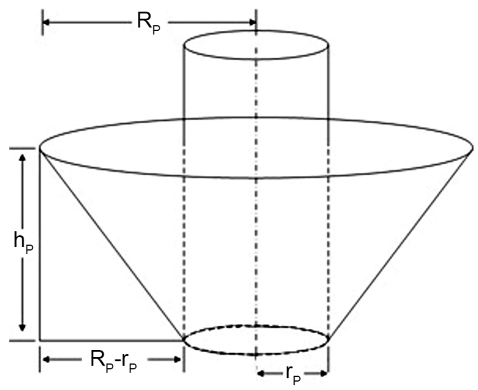

Fig. 2. Theoretical deformation geometry of the tested fabric.

TABLE I
LINGUISTIC FUZZY SETS FOR THE INPUT-OUTPUT PARAMETERS

Type	Parameters	Range	Linguistic fuzzy sets
Input	Fabric areal weight (g/m^2)	446-690	Low, medium, medium-high, and high
	Needle penetration depth (mm)	10-14	Low, medium, and high
	Punch density ($1/cm^2$)	100-300	Low, medium, and high
Output	Puncture resistance (N)	1000-2580	PR_1, PR_2, …, PR_{14}, and PR_{15}
	Puncture real elongation (%)	53.8-98.4	PRE_1, PRE_2, …, PRE_{14}, and PRE_{15}

of the tested fabrics as output variables. For fuzzification, four possible linguistic variables namely low (L), medium (M), medium-high (MH), and high (H) for the input variable of fabric areal weight; three possible linguistic variables are known as low (L), medium (M) and high (H) for the input variable of needle penetration depth and three possible linguistic variables of low (L), medium (M) and high (H) for the input variable of punch density were chosen. Fifteen linguistic variables namely PR_1 to PR_{15} and PRE_1 to PRE_{15} were also considered for the output variables of puncture resistance and real elongation, respectively. The linguistic fuzzy sets, as shown in Table I, are able to cover properly the entire ranges of input and output parameters.

In the model, triangular membership functions were adopted for describing input and output variables because of their simplicity and computational efficiency. The triangular membership function is used to convert the linguistic values in the range of 0–1. The triangular formed membership functions for the fuzzy variables have been developed using MATLAB fuzzy toolbox as depicted in Fig. 3.

The next stage of the fuzzy inference system is the construction of the if-then rules, which are used to represent the fuzzy relationships between input and output fuzzy variables. In this study, for constructing the rule base of the fuzzy model, a total of 36 rules were utilized based on experts' experiences and data collected from the case study of the nonwoven needle-punched polyester fabrics. Some of the rules are shown in Tables II and III.

A "Mamdani" max-min inference approach was also used to aggregate the fuzzy sets into a single fuzzy set. Finally, the defuzzification method, known as the center of gravity, was applied to convert the fuzzy output into a non-fuzzy crisp numeric value according to Eq. (2).

IV. RESULTS AND DISCUSSION

Table IV represents the ANOVA statistical results. As seen, the analyzed independent variables have a high intensity of the significant effect on puncture resistance and puncture real elongation of the nonwoven samples (P_r<0.0001). On the other hand, the results denoted that there is not any interaction effect between independent variables at their studied levels.

A. Operation of the Fuzzy Prediction Model

The operation of the developed fuzzy model for prediction of puncture real elongation in a graphical method typically is shown in Fig. 4. For a simple demonstration, out of 36

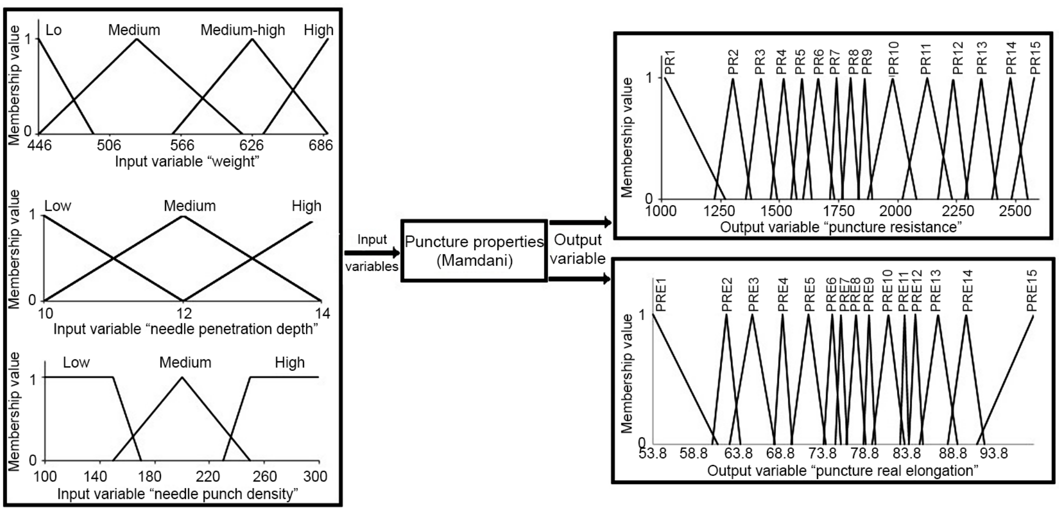

Fig. 3. Triangular membership curves of the input and output variables.

TABLE II
USED FUZZY RULES FOR PREDICTING PUNCTURE RESISTANCE

Number	Rule
1	If the fabric areal weight is low and needle penetration depth is low and punch density is low then puncture resistance is PR3.
2	If the fabric areal weight is low and needle penetration depth is low and punch density is medium then puncture resistance is PR3.
	.
	.
	.
35	If the fabric areal weight is high and needle penetration depth is high and punch density is medium then puncture resistance is PR11.
36	If the fabric areal weight is high and needle penetration depth is high and punch density is high then puncture resistance is PR10.

TABLE III
USED FUZZY RULES FOR PREDICTING PUNCTURE REAL ELONGATION

Number	Rule
1	If the fabric areal weight is low and needle penetration depth is low and punch density is low then puncture real elongation is PRE15.
2	If the fabric areal weight is low and needle penetration depth is low and punch density is medium then puncture real elongation is PRE15.
	.
	.
	.
35	If the fabric areal weight is high and needle penetration depth is high and punch density is medium then puncture real elongation is PRE3.
36	If the fabric areal weight is high and needle penetration depth is high and punch density is high then puncture real elongation is PRE1.

rules only one fuzzy rule has been depicted in the figure. According to this rule, if fabric areal weight, needle penetration depth, and punch density are considered medium-high, low, and high, respectively, then the output puncture real elongation will be PRE10. For instance, if the areal weight of the fabric is 621 g/m^2, the needle penetration depth is 10 mm, and the punch density is 300 1/cm^2, then all 36 fuzzy rules are evaluated simultaneously to determine the fuzzy output puncture real elongation. After aggregation and defuzzification, the final crisp output puncture real elongation of the fuzzy set is found to be 81.4% as shown in Fig. 4.

B. Effect of Input Parameters on the Puncture Resistance

The relationships between fabric areal weight, needle penetration depth, and punch density on the input side and puncture resistance on the output side were characterized through surface plots as determined by the fuzzy logic model as shown in Fig. 5. Figs. 5a and 5b show that the puncture resistance increases with the enhancement of the

TABLE IV
ANOVA RESULTS OF THE USED FACTORIAL DESIGN OF EXPERIMENT

Response variable	Source	Df	Sum square	Mean square	F-value	Pr> F
Puncture resistance (N)	Fabric areal weight (g/m^2)	4	34918089.72	8729522.43	175.37	<0.0001
	Needle penetration depth (mm)	2	2753751.86	1376875.93	27.66	<0.0001
	Punch density (1/cm^2)	4	2642729.21	660682.33	13.27	<0.0001
	Error	289	14385996.09	49778.53	-	-
	Corrected total	299	54700566.99	-	-	-
Puncture real elongation (%)	Fabric areal weight (g/m^2)	4	2516.73	629.18	20.42	<0.0001
	Needle penetration depth (mm)	2	19027.03	9513.52	308.80	<0.0001
	Punch density (1/cm^2)	4	4735.58	1183.89	38.43	<0.0001
	Error	289	8903.64	30.81	-	-
	Corrected total	299	35182.98	-	-	-

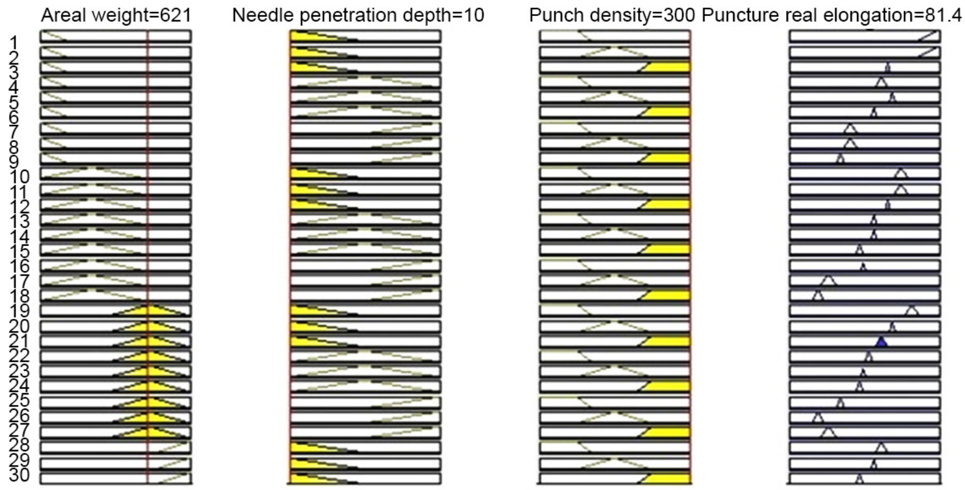

Fig. 4. A typical illustration for the operation of fuzzy prediction model.

fabric's areal weight, which is in agreement with the results of previous research [14]. This is mainly due to the more fibers in the cross-section of the fabric which can lead to increased lateral surfaces of the compressed fibers as well as fiber-to-fiber friction. As a result, the puncture resistance enlarges. As shown in Figs. 5a and 5c, although puncture resistance slightly increases with the enhancement of needle penetration depth from 10 mm to 12 mm, the contrast in behavior points increasing in this depth from 12 mm to 14 mm causes to decrease puncture resistance. According to the results of previous research [6], excessive increase of needle penetration depth causes more fiber breakage which is resulted to decrease in the puncture resistance. Figs. 5b and 5c also show that puncture resistance decreases when the punch density increases. This is due to the similar reason specified for the effect of the needle penetration depth.

C. Effect of Input Parameters on the Puncture Real Elongation

The relationship among the effects of input parameters on

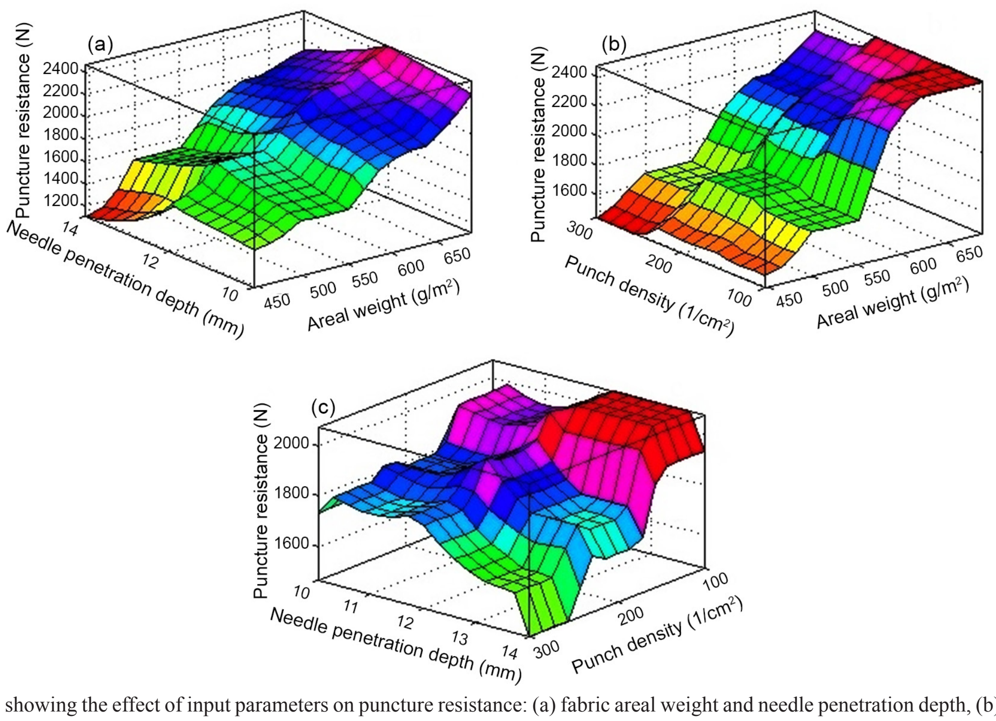

Fig. 5. Surface plots showing the effect of input parameters on puncture resistance: (a) fabric areal weight and needle penetration depth, (b) fabric areal weight and punch density, and (c) punch density and needle penetration depth.

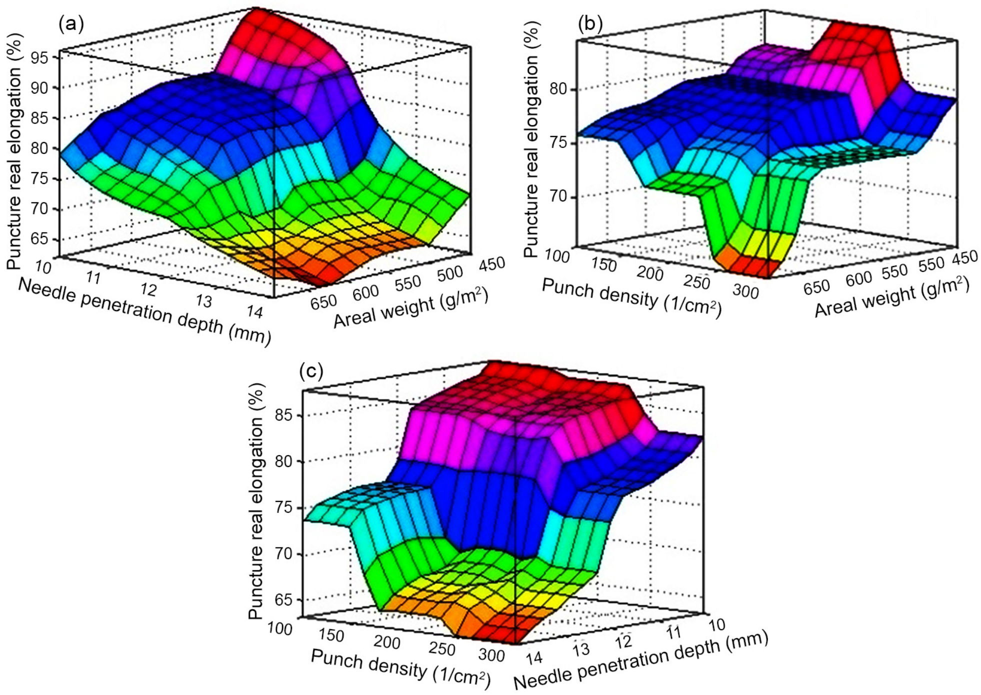

Fig. 6. Surface plots showing the effect of input parameters on puncture real elongation: (a) fabric areal weight and needle penetration depth, (b) fabric areal weight and punch density, and (c) punch density and needle penetration depth.

puncture real elongation is shown in Fig. 6. Considering the last figure, it can be noted that the higher value of all input variables causes to decrease in puncture real elongation of the fabric. More magnitudes of the input variables not only increase fiber to fiber frictional force but also cause that the fibers entanglements which do not permit their displacements to increase. Thereby, less elongation value of the puncture is expectable.

D. Validation of the Fuzzy Prediction Model

Evaluating the prediction accuracy of the proposed fuzzy model was performed using the values of mean absolute error percentage (MAEP) and correlation coefficient (R) according to Eqs. (4) and (5):

$$\text{MAEP} = \frac{1}{N}\sum_{i=1}^{i=N}\left[\frac{|E_a - E_p|}{E_a}\times 100\right] \tag{4}$$

$$R = \sqrt{1-\left[\frac{\sum_{i=1}^{i=N}(E_a - E_p)^2}{\sum_{i=1}^{i=N}(E_a - E_M)^2}\right]} \tag{5}$$

Where, E_a and E_p are the actual and predicted values, respectively. E_M is the mean value and N is considered as the number of samples.

The mean absolute error percentage (MAEP) gives a deviation between the predicted and actual values. The best value for the MAEP is zero. Much closer to zero indicates that the prediction accuracy is higher. The correlation coefficient (R) which checks the prediction performance of each model shows the correlation between the measured and predicted values.

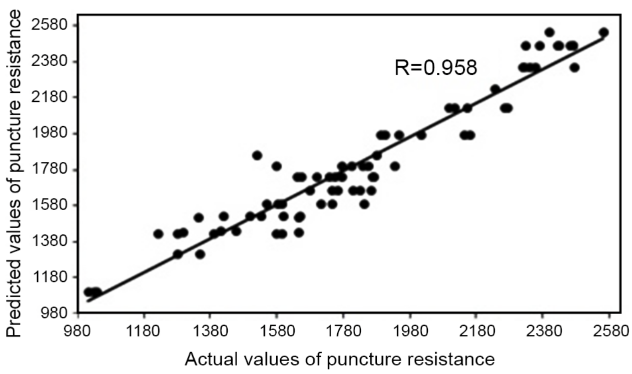

Fig. 7. Correlation between the actual and model predicted values of puncture resistance.

The results indicate that the mean absolute error percentage (MAEP) between the predicted and experimental values of puncture resistance and real elongation of the nonwoven needle-punched polyester fabrics are 5.02 and 3.14%, respectively. The correlation between the actual puncture properties and the relevant values predicted by the fuzzy model are depicted in Figs. 7 and 8. It can

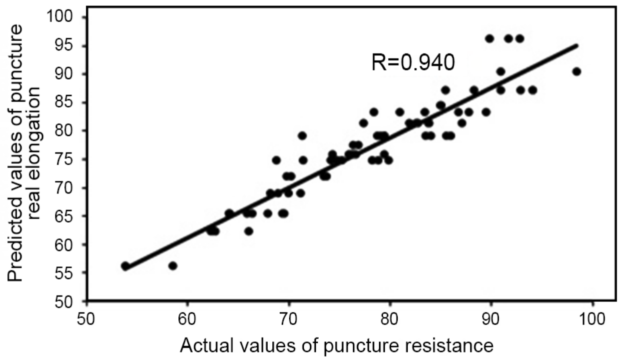

Fig. 8. Correlation between the actual and model predicted values of puncture real elongation.

be seen that the coefficient of correlation between actual values of the static puncture properties and predicted values of the fuzzy model are 95.8 and 94% for resistance and real elongation, respectively. It was also concluded that the anticipator model of the fuzzy logic has significant ability and accuracy to predict the puncture resistance and real elongation of the nonwoven needle-punched polyester fabrics.

V. CONCLUSION

In this study, fuzzy logic models were developed to evaluate puncture resistance and real elongation of nonwoven needle-punched polyester fabrics. Chosen factors for model input were considered the main processing parameters of fabric areal weight, needle penetration depth, and punch density. The surface plots showed that puncture resistance increases with the enhancement of fabric areal weight, but excessive increase of the needling parameters of needle penetration depth and punch density reduces the puncture resistance. Furthermore, the surface plots demonstrated that the fabric puncture real elongation decreased, while the input variables increased. The results also indicated that the mean absolute error percentage between the predicted and experimental values of puncture resistance and puncture real elongation of the tested fabrics was very low. In addition, the results also show that there is a good relationship between the actual and predicted values of the puncture properties. Generally, it was concluded that the puncture behavior of nonwoven needle-punch polyester fabrics can be predicted with high accuracy using the fuzzy logic model in the non-linear domain.

REFERENCES

[1] S. Debnath and M. Madhusoothanan, "Studies on compression behaviour of polypropylene needle punched nonwoven fabrics under wet condition", *Fiber Polym.*, vol. 14, no. 5, pp. 854-859, 2013.

[2] E. Çinçik and E. Koç, "The effect of blend ratio and process parameters on tensile properties of polyester/viscose blended needle-punched nonwovens", *Fiber Polym.*, vol. 14, no. 6, pp. 1040-1049, 2013.

[3] A. Rawal, S. Anand, and T. Shah, "Optimization of parameters for the production of needle punched nonwoven geotextiles", *J. Ind. Text.*, vol. 37, no. 4, pp. 341-356, 2008.

[4] C.F.J. Kuo, T.L. Su, and C.P. Tsai, "Optimization of the needle punching process for the nonwoven fabrics with multiple quality characteristics by grey-based taguchi method", *Fiber Polym.*, vol. 8, no. 6, pp. 654-664, 2007.

[5] A. Rawal and R. Anandjiwala, "Relationship between process parameters and properties of multifunctional needle punched geotextiles", *J. Ind. Text.*, vol. 35, no. 4, pp. 271-285, 2006.

[6] M. Miao, H.E. Glassey, and M. Rastogi, "An experimental study of the needled nonwoven process: part III: fiber damage due to needling", *Text. Res. J.*, vol. 74, no. 6, pp. 485-490, 2004.

[7] J.W.S. Hearle and A.T. Purdy, "2—the influence of the depth of needle penetration on needled-fabric structure and tensile properties", *J. Text. Inst.*, vol. 65, no. 1, pp. 6-12, 1974.

[8] J.W.S. Hearle, M.A.I. Sultan, and T.N. Choudhari, "9—A study of needled fabrics. Part II: effects of the needling process", *J. Text. Inst.*, vol. 59, no. 2, pp. 103-116, 1968.

[9] E. Saberi, S.S. Najar, S.B. Abdellahi, and Z. Soltanzadeh, "A hyperelastic approach for finite element modelling puncture resistance of needle punched nonwoven geotextiles", *Fiber Polym.*, vol. 18, no. 8, pp. 1623-1628, 2017.

[10] H. Mashroteh, E. Ekhtiyari, S. Fattahi, A. Aflatounian, H. Rahimi, and M. Sadeghi-Sadeghabad, "Behavior analysis of the nonwoven needle-punched polyester fabrics due to compression loading", *J. Text. Polym.*, vol. 7, no. 1, pp. 33-43, 2019.

[11] J.H. Lin, T.T. Li, and C.W. Lou, "Puncture-resisting, sound-absorbing and thermal-insulating properties of polypropylene-selvages reinforced composite nonwovens", *J. Ind. Text.*, vol. 45, no. 6, pp. 1477-1489, 2016.

[12] T.T. Li, R. Wang, C.W. Lou, and J.H. Lin, "Static and dynamic puncture behaviors of compound fabrics with recycled high-performance Kevlar fibers", *Compos. Part B-Eng.*, vol. 59, pp. 60-66, 2014.

[13] T.T. Li, R. Wang, C.W. Lou, C.H. Huang, and J.H. Lin, "Mechanical and physical properties of puncture-resistance plank made of recycled selvages", *Fiber*

Polym., vol. 14, no. 2, pp. 258-265, 2013.

[14] A.S. Askari, S.S. Najar, and Y.A. Vaghasloo, "Study the effect of test speed and fabric weight on puncture behavior of polyester needle punched nonwoven geotextiles", *J. Eng. Fiber. Fabr.*, vol. 7, no. 3, pp. 1-5, 2012.

[15] Y. Termonia, "Puncture resistance of fibrous structures", *Int. J. Impact. Eng.*, vol. 32, no. 9, pp. 1512-1520, 2006.

[16] T.K. Ghosh, "Puncture resistance of pre-strained geotextiles and its relation to uniaxial tensile strain at failure", *Geotext. Geomembranes*, vol. 16, no. 5, pp. 293-302, 1998.

[17] I. Hossain, I.A. Choudhury, A.B. Mamat, and A. Hossain, "Predicting the colour properties of viscose knitted fabrics using soft computing approaches", *J. Text. Inst.*, vol. 108, no. 10, pp. 1689-1699, 2017.

[18] I. Hossain, A. Hossain, and I.A. Choudhury, "Color strength modeling of viscose/Lycra blended fabrics using a fuzzy logic approach", *J. Eng. Fiber. Fabr.*, vol. 10, no. 1, pp. 158-168, 2015.

[19] A. Majumdar and A. Ghosh, "Yarn strength modelling using fuzzy expert system", *J. Eng. Fiber. Fabr.*, vol. 3, no. 4, 2008.

[20] B. Jaouachi and F. Khedher, "Evaluating sewing thread consumption of jean pants using fuzzy and regression methods", *J. Text. Inst.*, vol. 104, no. 10, pp. 1065-1070, 2013.

[21] H.T. Choi, S.H. Jeong, S.R. Kim, J.Y. Jaung, and S.H. Kim, "Detecting fabric defects with computer vision and fuzzy rule generation. Part II: defect identification by a fuzzy expert system", *Text. Res. J.*, vol. 71, no. 7, pp. 563-573, 2001.

[22] M.L. Huang, Y.H. Hung, and W.C. Kuo, "Combining taguchi method with fuzzy inference on process optimization for fiber manufacturing", *Fiber Polym.*, vol. 16, no. 12, pp. 2670-2681, 2015.

[23] E. Haghighat, M.S. Johari, and S.M. Etrati, "Study of the hairiness of polyester-viscose blended yarns. Part IV-predicting yarn hairiness using fuzzy logic", *Fibre. Text. East. Eur.*, vol. 3, no. 92, pp. 39-42, 2012.

[24] N. Dehghan-Manshadi and M. Hadizadeh, "Applying fuzzy logic model for bending rigidity evaluation of woven fabrics", *J. Text. Polym.*, vol. 7, no. 1, pp. 61-68, 2019.

[25] M. Kabbari, F. Fayala, A. Ghith, and N. Liouane, "Predicting stain repellency characteristics of knitted fabrics using fuzzy modeling and surface response methodology", *J. Text. Inst.*, vol. 108, no. 5, pp. 683-691, 2017.

[26] S.E.G. Jeguirim, A.B. Dhouib, M. Sahnoun, M. Cheikhrouhou, L. Schacher, and D. Adolphe, "The use of fuzzy logic and neural networks models for sensory properties prediction from process and structure parameters of knitted fabrics", *J. Intell. Manuf.*, vol. 22, no. 6, pp. 873-884, 2011.

[27] F. Abidi, T. Harizi, S. Msahli, and F. Sakli, "Modelling of Tunisian hand-made carpet resilience under long static loading using fuzzy expert system", *Fiber Polym.*, vol. 18, no. 9, pp. 1810-1815, 2017.

[28] S.N. Sivanandam, S. Sumathi, and S.N. Deepa, "Introduction to fuzzy logic using MATLAB", vol. 1, Berlin: Springer, 2007.

[29] E. Haghighat, S.S. Najar, and S.M. Etrati, "The prediction of needle penetration force in woven denim fabrics using soft computing models", *J. Eng. Fiber. Fabr.*, vol. 9, no. 4, 2014.