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Modelling the Effect of Resin-Finishing Process Variables on the Dimensional Stability and Bursting Strength of Viscose Plain Knitted Fabric Using a Fuzzy Expert System

Modeliranje vpliva spremenljivk postopka plemenitenja s smolo na dimenzijsko stabilnost in razpočno trdnost viskoznega pletiva z uporabo sistema mehke logike

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Abstract

The application of cross-linking resin is an effective method for improving and controlling dimensional stability, such as the shrinkage of viscose single jersey knits. However, such treatment often leads to a significant deterioration in the bursting strength of treated fabrics. In this regard, resin treatment using a softening agent can be an additional potential solution for retaining the bursting strength of treated fabrics. Resin treatment is one kind of chemical finishing process that inhibits cellulosic textile fibre swelling during wetting, provides fibre resistance to deformation and prevents shrinkage. The key objective of this study was to model the effect of resin-finishing process variables for predicting the shrinkage control and bursting strength of viscose single jersey knitted fabrics. The MATLAB (Version 8.2.0.701) fuzzy expert system was used to model the optimum resin and softener concentrations, as well as the best curing time for the prediction of maximum shrinkage control with a minimum loss in fabric bursting strength. The optimal process variables were found to be a resin concentration of 75 g/l, a softener concentration of 45 g/l and a curing time of 225 seconds. The fuzzy expert model developed in this study was validated using experimental data. It was found that the model has the ability and accuracy to predict fabric shrinkage and bursting strength effectively in the non-linear field.

Keywords: cellulose, modelling, FES model, fuzzy inference, dyeing, textiles

Izvleček

Uporaba zamreževalne smole je ena izmed učinkovitih metod za izboljšanje in nadzor dimenzijske stabilnosti, kot je krčenje viskoznih levo-desnih pletiv. Obdelava s smolo je kemični postopek, ki zavira nabrekanje celuloznih tekstilnih vlaken v mokrem in zagotavlja odpornost vlaken proti deformiranju ter zavira krčenje. Vendar takšna obdelava po-

gosto močno poslabša razpočno trdnost obdelanih tkanin. Uporaba mehčalca je lahko ena od rešitev za ohranjanje razpočne trdnosti z zamreževalno smolo obdelanih pletiv. Ključni cilj raziskave je bil modelirati vplivne spremenljivke plemenitilnega postopka s smolo za napovedovanje nadzora krčenja in razpočne trdnosti enojnih pletiv iz viskoznih vlaken. Za napovedovanje nadzora maksimalnega krčenja ob minimalnem znižanju razpočne trdnosti pletiva je bil uporabljen mehki ekspertni sistem @ MATLAB (različica 8.2.0.701), s katerim so bili modelirani optimalni koncentraciji smole in mehčalca ter najugodnejši čas zamreževanja. Ugotovljene optimalne spremenljivke procesa so koncentracija smole 75 g/l, koncentracija mehčalca 45 g/l in čas strjevanja 225 s. Razviti mehki ekspertni model je bil potrjen z eksperimentalnimi podatki. Ugotovljeno je bilo, da ima model zmožnost in natančnost predvidevanja krčenja in razpočne trdnosti pletiva v nelinearnem območju.

Ključne besede: celuloza, modeliranje, model FES, mehko sklepanje, barvanje tekstilij

1 Introduction

Viscose is the first and foremost the oldest regenerated cellulose fibre produced using the wet spinning process. Viscose, however, is the most absorbent and highly reactive among all cellulose fibres. Globally speaking, knitted fabrics made of viscose fibres are very popular for fashionable apparel because of their lower price and amazing quality characteristics, such as rich brilliant colour, superior moisture absorbance, wear comfort, softness against the skin, and easy-care properties relative to cotton knit and woven fabrics [1–5]. However, poor dimensional stability is a well-known concern in viscose knitwear, even after decades of development in modern manufacturing methods [6]. Although almost all single-knit structures demonstrate a major propensity to shrink, single-knit structures made of viscose fibre are subject to extreme shrinkage, mainly in terms of length, because of its relatively lower crystalline and more amorphous structure than that of cotton fibre [1–3, 7]. Many studies have reported improvements in the poor dimensional stability of knitted fabrics. Reeves and Frank proposed that the shrinkage of cotton knitted fabrics could be reduced by any treatment that prevents cotton fibre swelling during wetting [8]. Candan and Onal reported that knitted fabrics made from open-end rotor yarns exhibit better dimensional stability than those made from ring-spun yarn [9]. However, open-end rotor yarns are not usually available in higher fineness and result in lower bursting strength than ring-spun yarn, thus limiting their use in knitted fabrics [10]. In another study, Candan and Onal reported that dimensional stability can be improved by decreasing the loop length of knitted fabrics. However, decreasing loop length in knitted fabrics is only practical to a certain extent, as knitting machines may not work properly after a further decrease. In the same study, Candan and Onal proposed

that the application of elastomeric yarns may be a good solution to poor dimensional stability. However, such an option is not always economical because of the cost considerations of elastane and the supplementary heat-setting process [9]. Moghassem and Tayebi mentioned that mercerization is one method used to improve the dimensional stability of cotton knits. Apart from the cost, the limited availability of a proper mercerization method for knits and quality control issues limit the mercerization process [11]. Safdar et al. mentioned that mechanical compaction using a compactor machine is a successful method for improving dimensional stability, but with limited shrinkage control, which may not last more than 4–5 washes [12]. Moreover, tumble drying is one way to control the dimensional stability of knitted garments [13–14]. However, lesser production and batch-to-batch quality variations of the tumble-drying method limit its use for improving dimensional stability [12]. In this regard, the application of cross-linking resin such as dimethylol dihydroxy ethylene urea (DMDHEU) is an additional potential solution for improving and controlling the dimensional stability problem of viscose jersey knits [3, 15]. A DMDHEU cross-linking agent is most widely-used for textile cellulosic fibre because it demonstrates good durable press properties at a low cost, is less detrimental to fabric strength, results in less discoloration, is post-curable, and yields low chlorine retention characteristics relative to other agents. Cross-linking happens within accessible fibre regions, providing fibre resistance to deformation, and improved elastic recovery from deformation. Cross-linking prevents fibre molecule movement during stress and prevents shrinkage. DMDHEU reacts with cellulose in the presence of a catalyst to form cross-links between individual cellulose chain molecules during resin treatment. In fact, cross-links occur between the four hydroxyl (-OH) groups of DMDHEU and single hydroxyl (-OH) group

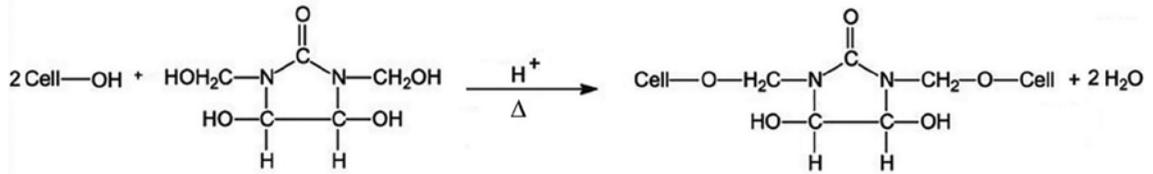


Figure 1: Cross-linking between DMDHEU and cellulose

of individual cellulose chain molecules. The reaction mechanism for cross-linking between DMDHEU and cellulose is shown in Figure 1 [16].

However, the use of such resin leads to a significant deterioration in the bursting strength of treated fabrics. This problem becomes even more severe when cross-linking products are used to control the shrinkage of open-structure fabrics, as well as high absorbent and more amorphous structure fibre fabric such as viscose single knit fabrics [2–3]. This is because a higher concentration of the cross-linking agent is required to control the high level of shrinkage in such structured fibre fabrics. Moreover, resins make the fabrics stiffer and harsh to the touch. In this regard, the application of softening agents through polyethylene emulsion can help to retain a fabric’s strength. Thus, in such cases, a critical balance must be maintained to attain the optimum dimensional stability in viscose knits with a minimum loss in fabric bursting strength [3]. Likewise, factors involving optimal shrinkage controlling with the desired bursting strength are resin concentration, softener concentration and curing time in the resin-finishing process. Therefore, the control of process parameters during the resin-finishing process is important for obtaining final products that meet customers’ requirement [17]. Moreover, all these factors perform non-linearly and interact with each other. It is thus very challenging for scientists and engineers to control resin-finishing processes. For this reason, it is not easy to create an exact model between process parameters and quality characteristics [4, 18, 19].

A conventional trial-and-error experimental approach did not succeed in this regard due to the major loss of time and resources [3]. Similarly, modelling based on mathematical and statistical techniques is not suitable because of its inability to capture the non-linear relationship between inputs and outputs. Alternatively, developing a prediction model using artificial neural network (ANN) and adaptive neuro-inference system (ANFIS) techniques is also a challenging and time-consuming process due to the large volume of trial data [18–21].

In this context, a fuzzy expert system (FES) is the scientific and engineering solution for quality modelling, as FES performs remarkably well with small amounts of experimental data in a non-linear, trial-and-error and complex textile domain [18–20, 22]. Moreover, a fuzzy logic model is more reasonable, cheaper in terms of design cost and often easier to apply than other models [18, 20–23]. Therefore, the main objective of this study was to develop a fuzzy resin model to achieve optimum dimensional stability in viscose knits with a minimum loss in fabric bursting strength as a function of resin concentration, softener concentration and curing time, which has not been reported in past studies.

2 Materials and methods

2.1 Fuzzy expert system

A fuzzy expert system is an artificial intelligence derived from fuzzy set theory established by Zadeh in 1965 [20, 21, 24]. The basic components of a fuzzy expert system are a fuzzifier, a fuzzy rule base, an inference engine and a defuzzifier as depicted in Figure 2.

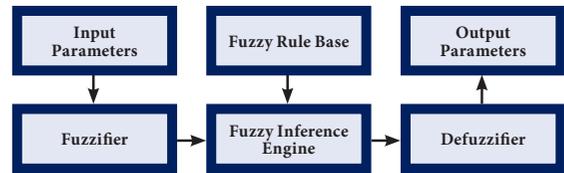


Figure 2: Basic structure of a fuzzy expert system [19]

Fuzzifier

A fuzzifier is the first block in fuzzy modelling, which converts all crisp numeric inputs into fuzzy numbers in a range from 0 to 1 using membership functions. A membership function is typically a curve that converts the numerical values of input variables into a fuzzy number in a range from 0 to 1. This value is called a membership value. Among various forms of membership functions, the triangle membership function is the simplest and most frequently used due to its accuracy [20, 24].

Fuzzy rule base

The fuzzy rules are the heart of fuzzy modelling and are expressed by if-then statements that narrate the input variables in the antecedent part and output variables in the consequent part, which determines the input-output relationship of the model [19, 20, 24]. As an expression, when a fuzzy model with two inputs and one output involves n fuzzy rules, the development of fuzzy rules can be presented as follows:

- Rule 1: If x is A_1 and y is B_1 , then z is C_1
- Rule 2: If x is A_2 and y is B_2 , then z is C_2
- ...
- Rule n: if x is A_n and y is B_n , then z is C_n ,

where x, y, and z are the linguistic variables representing the input variables and the output variable respectively, and A_i, B_i and $C_i (i = 1, 2 \dots n)$ are the fuzzy numbers that represent the linguistic states.

Inference engine

The fuzzy inference engine is fundamentally a control mechanism that plays a central role in fuzzy modeling because of its human decision-making ability. Most commonly, the Mamdani max-min fuzzy inference mechanism is used to aggregate several fuzzy sets into a single fuzzy set because it assures a linear interpolation of the output between the rules [1, 20, 24]. For three-input and three-output fuzzy systems, the fuzzy inference mechanism can be presented graphically as bellows in Figure 3[1].

RC (resin concentration), SC (softener concentration) and CT (curing time) are in inputs side and LS (lengthwise shrinkage), WS (widthwise shrinkage) and BS (bursting strength) are on the output side.

Defuzzifier

A defuzzifier is the fourth and last block of the fuzzy expert system and converts the fuzzy inference out-

put into a non-fuzzy value z. Among various defuzzification methods, the centre of gravity method is most frequently used [2, 20, 24] and is calculated using equation 2 below.

$$z = \frac{\sum_{i=1}^n (\mu_i * b_i)}{\sum_{i=1}^n \mu_i} \tag{1}$$

where b_i represents the position of the singleton in the i th universe and μ_i is equal to the firing strength of truth values of rule $i (i = 1, 2 \dots n$ and $n =$ number of observations). The firing strength of a rule is the product of the input membership grades. This value is passed to the membership grade of the output to the corresponding fuzzy set. A universe is the set of entities over which certain variables of interest in some formal treatment may range. A singleton is an individual member or thing distinct from others grouped with it.

2.2 Development of a fuzzy resin model

In order to develop a fuzzy resin model of viscose knitted fabrics, resin concentration (RC), softener concentration (SC) and curing time (CT) were used as input variables, while lengthwise shrinkage (LS), width-wise shrinkage (WS) and bursting strength (BS) were used as output variables. These resin-finishing process variables were chosen exclusively, as they have a significant effect on fabric shrinkage and bursting strength. A fuzzy logic toolbox from MATLAB R2013b (version 8.2.0.701) was used to create the proposed fuzzy resin model of shrinkage and bursting strength. The construction of a fuzzy resin modelling for shrinkage and bursting strength is depicted in Figure 4.

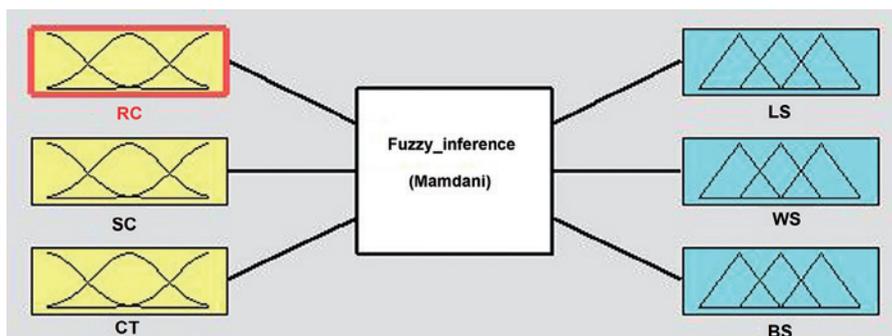


Figure 3: Fuzzy inference mechanism (Mamdani)

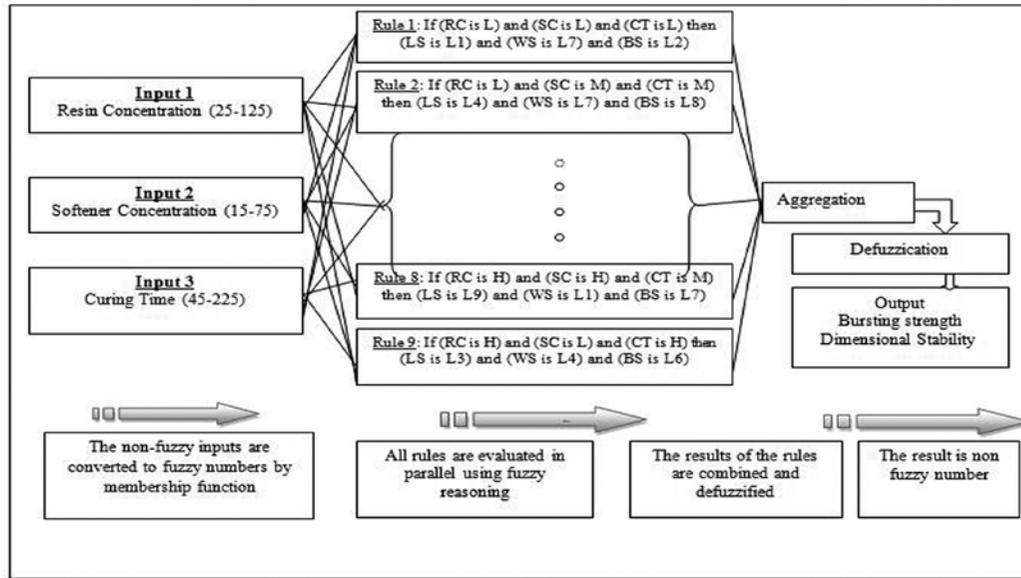


Figure 4: Schematic representation of a fuzzy expert system for the modelling of dimensional stability and bursting strength

For fuzzification, three possible linguistic fuzzy sets, namely low (L), medium (M), and high (H), were chosen for the input variables RC, SC and CT. Likewise, nine output linguistic fuzzy sets, i.e. from L1 to L9 (Level 1, Level 2 ... Level 9) were considered for LS, WS and BS. In the present study, triangular shaped membership functions were used for both input and output variables due to their accuracy [18, 20]. Moreover, a Mamdani max-min inference approach and the centre of gravity defuzzification method were applied in this work. The selection of the number of membership functions and their initial values was based on the system knowledge and experimental conditions [18, 20]. There is a level of membership for each linguistic word that is applied in each input variable. Equations 2-7 were used for fuzzification, as shown in Figures 5-10.

$$RC(i_1) = \begin{cases} i_1, & 25 \leq i_1 \leq 125 \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

$$SC(i_2) = \begin{cases} i_2, & 15 \leq i_2 \leq 75 \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

$$CT(i_3) = \begin{cases} i_3, & 45 \leq i_3 \leq 225 \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

$$LS(o_1) = \begin{cases} o_1, & 1.6 \leq o_1 \leq 6.7 \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

$$WS(o_2) = \begin{cases} o_2, & 0.2 \leq o_2 \leq 2 \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

$$BS(o_3) = \begin{cases} o_3, & 270 \leq o_3 \leq 318 \\ 0, & \text{otherwise} \end{cases} \quad (7)$$

where i_1 , i_2 and i_3 represent the first (RC), second (SC) and third (CT) input variables respectively and o_1 , o_2 and o_3 represent the output variables (LS), (WS) and (BS), as shown in equations 2-7.

The triangular formed membership functions for the fuzzy variables RC, SC, CT, LS, WS and BS were developed using the MATLAB Fuzzy Toolbox as shown in Figures 5-10. The membership functions for input variable RC were constructed using the linguistic fuzzy sets low (L), medium (M), and high (H) with values of RC (25 g/l, 75 g/l and 125 g/l) as depicted in Figure 5. Likewise, the membership functions for input variables SC and CT were created by taking the fuzzy numbers low (L), medium (M) and high (H) with values of SC (15 g/l, 45 g/l and 75 g/l) and CT (45 s, 135 s, 225 s), respectively, as illustrated in Figures 6-7. In the same way, the membership functions for the output variables LS, WS and BS were formed using the fuzzy numbers Level 1, Level 2, Level 3, Level 4, Level 5, Level 6, Level 7, Level 8 and Level 9 with value ranges LS (1.6-6.7%), WS (0.2-2%) and BS (270-318 kPa), respectively, as shown in Figures 8-10. The values were given in such a way that they were equally spaced and covered the whole input and output space. The values of input and output variables were selected based on the expert system knowledge, previous experience and arbitrary choice.

From a textile point of view and previous experience, it is known that output variable shrinkage is related to input variable resin concentration. This is because shrinkage is efficiently decreased due to the formation of a cross-link between cellulose and resin, while the output variable bursting strength is influenced by the input variable softener concentration. The reason lies

in the fact that softener compensates for the loss of bursting strength during resin application. Moreover, the input variables resin concentration and softener concentration have a synergetic effect with curing time. After fuzzification, a total of 9 fuzzy rules were created based on expert knowledge and previous experience, as presented in Table 1.

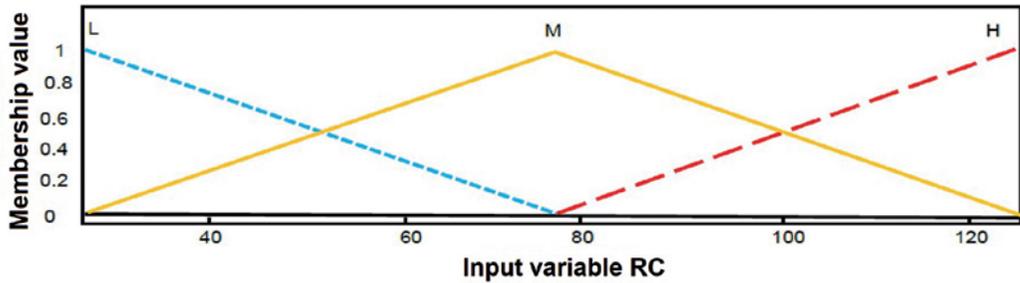


Figure 5: Membership function of RC

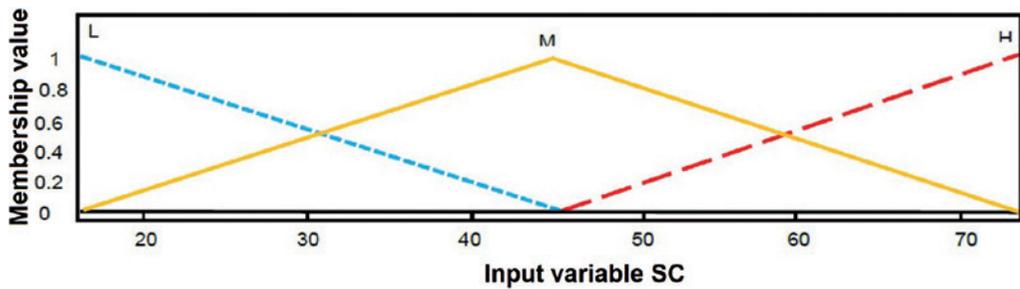


Figure 6: Membership function of SC

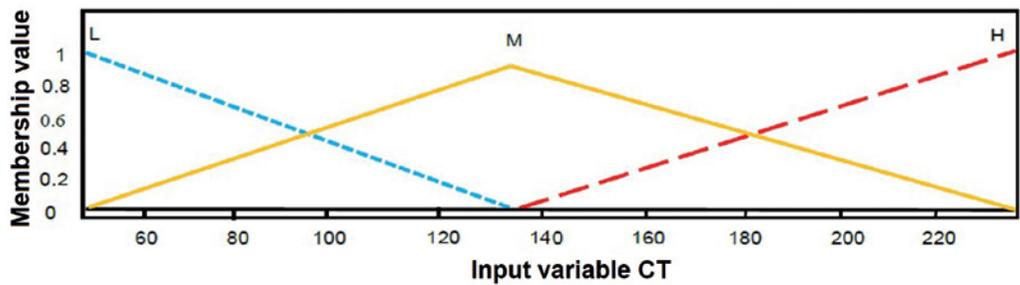


Figure 7: Membership function of CT

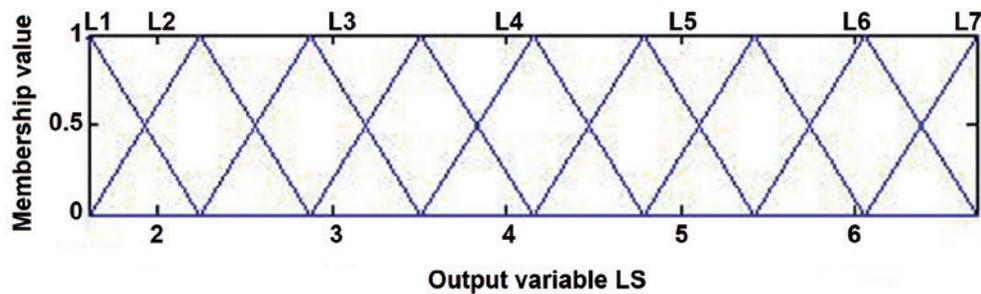


Figure 8: Membership function of LS

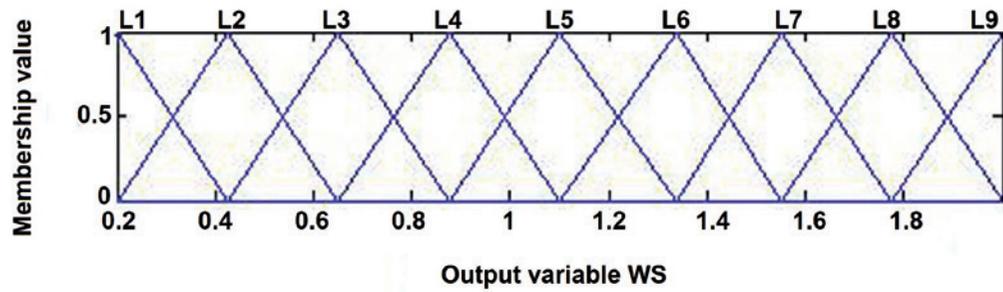


Figure 9: Membership function of WS

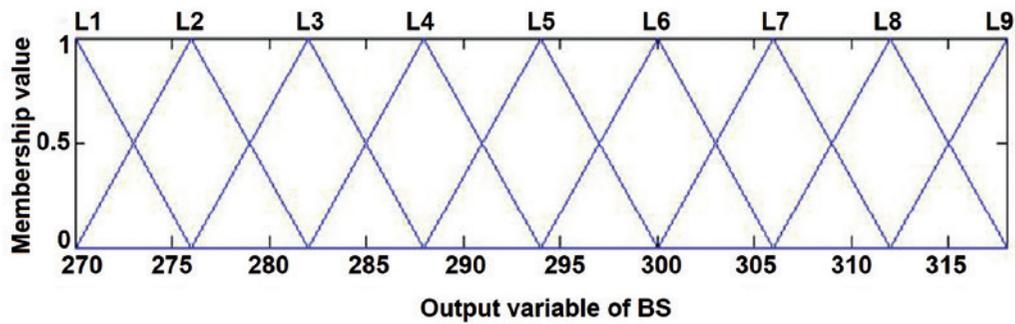


Figure 10: Membership function of BS

Table 1: Fuzzy inference rules

Rules no.	Input variables			Output variables		
	RC	SC	CT	LS	WS	BS
1	L	L	L	L1	L7	L2
2	L	M	M	L4	L7	L8
3	L	H	H	L7	L8	L3
4	M	M	M	L5	L5	L5
5	M	L	M	L1	L9	L9
6	M	M	H	L8	L1	L8
7	H	M	L	L9	L1	L4
8	H	H	M	L9	L1	L7
9	H	L	H	L3	L4	L6

The calculation of the membership values for the developed membership functions of RC, SC and CT based on the Figures 5-10, created rules and the equations presented above (2-7) is presented as follows:

$$\mu_L(\text{RC}) = \begin{cases} \frac{75 - i_1}{75 - 25}; & 25 \leq i_1 \leq 75 \\ 0; & i_1 \geq 75 \end{cases} \quad (8)$$

From equation 8:

If we put $i_1=25$ then,

$$\mu_L(\text{RC}) = \left(\frac{75 - 25}{75 - 25} \right) = \frac{50}{50} = 1 \quad (8a)$$

If we put $i_1=50$ then,

$$\mu_L(\text{RC}) = \left(\frac{75 - 50}{75 - 25} \right) = \frac{25}{50} = 0.5 \quad (8b)$$

If we put $i_1=75$ then,

$$\mu_L(\text{RC}) = \left(\frac{75 - 75}{75 - 25} \right) = \frac{0}{50} = 0$$

$$\mu_M(\text{RC}) = \begin{cases} \frac{i_1 - 25}{75 - 25}; & 25 \leq i_1 \leq 75 \\ \frac{125 - i_1}{125 - 75}; & 75 \leq i_1 \leq 125 \\ 0; & i_1 \geq 125 \end{cases}$$

From equation 9:

If we put $i_1=25$ then,

$$\mu_M(\text{RC}) = \left(\frac{25 - 25}{75 - 25} \right) = \frac{0}{50} = 0 \quad (9a)$$

If we put $i_1=75$ then,

$$\mu_M(\text{RC}) = \left(\frac{75 - 25}{75 - 25} \right) = \frac{50}{50} = 1 \quad (9b)$$

If we put $i_1=125$ then,

$$\mu_M(\text{RC}) = \left(\frac{125 - 125}{125 - 75} \right) = \frac{0}{50} = 0 \quad (9c)$$

$$\mu_H(\text{RC}) = \begin{cases} \frac{i_1 - 75}{125 - 75}; & 75 \leq i_1 \leq 125 \\ 0; & i_1 \leq 75 \end{cases} \quad (10)$$

From equation10:

If we put $i_1=75$ then,

$$\mu_H(\text{RC}) = \left(\frac{75 - 75}{125 - 75} \right) = \frac{0}{50} = 0 \quad (10a)$$

If we put $i_1=100$ then,

$$\mu_H(\text{RC}) = \left(\frac{100 - 75}{125 - 75} \right) = \frac{25}{50} = 0.5 \quad (10b)$$

If we put $i_1=125$ then,

$$\mu_H(\text{RC}) = \left(\frac{125 - 75}{125 - 75} \right) = \frac{50}{50} = 1 \quad (10c)$$

$$\mu_L(\text{SC}) = \begin{cases} \frac{45 - i_2}{45 - 15}; & 15 \leq i_2 \leq 45 \\ 0; & i_2 \geq 45 \end{cases} \quad (11)$$

From equation 11:

If we put $i_2=15$ then,

$$\mu_L(\text{SC}) = \left(\frac{45 - 15}{45 - 15} \right) = \frac{30}{30} = 1 \quad (11a)$$

If we put $i_2=30$ then,

$$\mu_L(\text{SC}) = \left(\frac{45 - 30}{45 - 15} \right) = \frac{15}{30} = 0.5 \quad (11b)$$

If we put $i_2=45$ then,

$$\mu_L(\text{SC}) = \left(\frac{45 - 45}{45 - 15} \right) = \frac{0}{30} = 0 \quad (11c)$$

$$\mu_M(\text{SC}) = \begin{cases} \frac{i_2 - 15}{45 - 15}; & 15 \leq i_2 \leq 45 \\ \frac{75 - i_2}{75 - 45}; & 45 \leq i_2 \leq 75 \\ 0; & i_2 \geq 75 \end{cases} \quad (12)$$

From equation12:

If we put $i_2=15$ then,

$$\mu_M(\text{SC}) = \left(\frac{15 - 15}{45 - 15} \right) = \frac{0}{30} = 0 \quad (12a)$$

If we put $i_2=45$ then,

$$\mu_M(\text{SC}) = \left(\frac{45 - 15}{45 - 15} \right) = \frac{30}{30} = 1 \quad (12b)$$

If we put $i_2=75$ then,

$$\mu_M(\text{SC}) = \left(\frac{75 - 75}{75 - 45} \right) = \frac{0}{30} = 0 \quad (12c)$$

$$\mu_H(\text{SC}) = \begin{cases} \frac{i_2 - 45}{75 - 45}; & 45 \leq i_2 \leq 75 \\ 0; & i_2 \leq 45 \end{cases} \quad (13)$$

From equation13:

If we put $i_2=45$ then,

$$\mu_H(\text{SC}) = \left(\frac{45 - 45}{75 - 45} \right) = \frac{0}{30} = 0 \quad (13a)$$

If we put $i_2=60$ then,

$$\mu_H(\text{SC}) = \left(\frac{60 - 45}{75 - 45} \right) = \frac{15}{30} = 0.5 \quad (13b)$$

If we put $i_2=75$ then,

$$\mu_H(\text{SC}) = \left(\frac{75 - 45}{75 - 45} \right) = \frac{30}{30} = 1 \quad (13c)$$

$$\mu_L(\text{CT}) = \begin{cases} \frac{135 - i_3}{135 - 45}; & 45 \leq i_3 \leq 135 \\ 0; & i_3 \geq 135 \end{cases} \quad (14)$$

From equation 14:

If we put $i_3=45$ then,

$$\mu_L(CT) = \left(\frac{135 - 45}{135 - 45} \right) = \frac{90}{90} = 1 \quad (14a)$$

If we put $i_3=90$ then,

$$\mu_L(CT) = \left(\frac{135 - 90}{135 - 45} \right) = \frac{45}{90} = 0.5 \quad (14b)$$

If we put $i_3= 135$ then,

$$\mu_L(CT) = \left(\frac{135 - 135}{135 - 45} \right) = \frac{0}{90} = 0 \quad (14c)$$

$$\mu_M(CT) = \begin{cases} \frac{i_3 - 45}{135 - 45}; & 45 \leq i_3 \leq 135 \\ \frac{225 - i_3}{225 - 135}; & 135 \leq i_3 \leq 225 \\ 0; & i_3 \geq 225 \end{cases} \quad (15)$$

From equation15:

If we put $i_3=45$ then,

$$\mu_M(CT) = \left(\frac{45 - 45}{135 - 45} \right) = \frac{0}{90} = 0 \quad (15a)$$

If we put $i_3= 135$ then,

$$\mu_M(CT) = \left(\frac{135 - 45}{135 - 45} \right) = \frac{90}{90} = 1 \quad (15b)$$

If we put $i_3=225$ then,

$$\mu_M(CT) = \left(\frac{225 - 225}{225 - 135} \right) = \frac{0}{90} = 0 \quad (15c)$$

$$\mu_H(CT) = \begin{cases} \frac{i_3 - 135}{225 - 135}; & 135 \leq i_3 \leq 225 \\ 0; & i_3 \leq 135 \end{cases} \quad (16)$$

From equation16:

If we put $i_3=135$ then,

$$\mu_H(CT) = \left(\frac{135 - 135}{225 - 135} \right) = \frac{0}{90} = 0 \quad (16a)$$

If we put $i_3=180$ then,

$$\mu_H(CT) = \left(\frac{180 - 135}{225 - 135} \right) = \frac{15}{90} = 0.5 \quad (16b)$$

If we put $i_3= 225$ then,

$$\mu_H(CT) = \left(\frac{225 - 135}{225 - 135} \right) = \frac{90}{90} = 1 \quad (16c)$$

Similarly, the membership value of other variables can be calculated. To demonstrate how the membership values of the developed membership functions from Figures 5-7 are determined, the following equations were explained.

Equation 11: If we put RC = 75 g/l, then one membership function $\mu_M(RC)$ is mapped and $\mu_M(RC)$ is found to be 1 from the equation (9b).

Equation 17: If we put SC = 45 g/l, then one membership function $\mu_M(SC)$ is mapped and $\mu_M(SC)$ is determined as 1 from the equation (12b).

Equation 23: If we put CT = 135 s, then one membership function $\mu_M(CT)$ is mapped and $\mu_M(CT)$ is calculated as 1 from the equation (15b).

From the above equations (9b), (12b) (15b), it evident that if RC is M, SC is M and CT is M, then rule 4 is to be fired. In the defuzzification stage, the truth degrees (μ) of each rule are counted with the help of the min and by taking the max between the active rules [21]. The firing strength (μ) of input variables for rule 4 is calculated as follows:

$$\mu_4 = \min\{\mu_M(RC), \mu_M(SC), \mu_M(CT)\} = \min(1, 1, 1) = 1 \quad (17)$$

The crisp output was subsequently counted. Haghghat et al. stated that in many circumstances, for a system whose output is a fuzzy set, it is essential to aggregate several fuzzy sets into a single fuzzy set using an aggregation method [24]. Finally, by using equations (1) and (17) with Figure 8, the crisp output of lengthwise shrinkage (LS) is calculated as shown below:

$$LS^{\text{crisp}} = \frac{1 \times 4.15}{1} = 4.15 \quad (18)$$

Prediction performance measure

The prediction accuracy of the developed model was investigated using a global prediction error, such as mean absolute error (MAE) and coefficient of determination (R^2). The formulations of those accuracy measures are given below.

$$MAE = \frac{1}{N} \sum_{i=1}^{i=N} \left(\frac{|E_a - E_p|}{E_a} \times 100 \right) \quad (19)$$

$$R^2 = 1 - \left(\frac{\sum_{i=1}^{i=N} (E_a - E_p)^2}{\sum_{i=1}^{i=N} (E_a - E_M)^2} \right) \quad (20)$$

where E_a represents the actual result, E_p represents the predicted result, E_M represents the mean value and N represents the number of observations.

The coefficient of determinations (R^2) compares the accuracy of the model to the accuracy of a standard model. The mean absolute error (MAE) gives the deviation between the predicted and experimental values and is required to reach zero [18].

2.3 Experimental work for the validation of the fuzzy resin model

Fabrics

The fabric used in this study was a single jersey viscose knit structure with a mass per unit area of 190 g/m². The fabric was knitted on a Pailung single jersey circular knitting machine, with a 30-inch (76.2 cm) diameter, and E20 and 90 yarn feeders.

Chemicals

The chemicals used in this study include: Felosan NOF as a wetting agent (CHT, Bangladesh), Kappavon CL as an anti-creasing agent (Kapp-Chemie, Bangladesh), Sirrix 2UD as a sequestering agent (Clariant, Bangladesh), Kappazon H53 as a peroxide stabilizer (Kapp-Chemie, Bangladesh), Reaknit FF(DMDHEU) as a cellulose cross-linking resin (CHT, Bangladesh), Polysiligen as silicon softener (CHT, Bangladesh), MgCl₂ as a catalyst, sodium carbonate, H₂O₂ and acetic acid, all of commercial grade.

Machinery and equipment

The following machinery and equipment were used: a Slavos sample winch dyeing machine (Greece), an Ehwa suntex platinum pin stenter with padding mangle (Korea), a Lafer compactor (Italy), a Wascator washing machine (SDL, England) and a Pneumatic Bursting tester (SDL, England).

Fabric pre-treatment

Viscose is a regenerated cellulose fibre that is free from natural impurities, such as fat, oil and wax.

However, it contains residual chemicals, such as sulfur and spinning lubricant that were used in the viscose manufacturing stage. Hence, mild pre-treatment is performed for viscose fibre to remove the aforementioned residual chemicals and added impurities. The fabric samples were subjected to pre-treatment in an industrial-scale winch dyeing machine at 90 °C for 30 minutes using an anti-creasing agent (Kappavon CL 1.0 g/l), sequestering agent (Kappquest FE, 0.5 g/l), wetting agent (Felosan NOF 1.0 g/l), soda ash (2.5 g/l), Hydrogen peroxide 50% (1.0 g/l) and stabilizing agent (Kappazon H53 0.3 g/l). Finally, the pre-treated fabric was hot washed, rinsed and neutralized using 1.0 g/l acetic acid and dried.

Resin finishing

The industrial-scale pre-treated fabrics were divided into nine samples (each 10 kg) that were subjected to resin finishing treatments on an open stenter padder at 75% pick-up according to a set of values for resin concentration (25 g/l, 75 g/l and 125 g/l), softener concentration (15 g/l, 45 g/l and 75 g/l), and curing time (45 s, 135 s and 225 s) under the experimental conditions shown in Table 2, followed by drying at 120 °C for 2.5 minutes and curing at 170 °C for the times specified in the experimental conditions, and finally compacted perfectly. The recipes were prepared with the specified amount of resin, softener and MgCl₂ catalyst (20% of the amount of resin used as recommended by the resin manufacturer).

Measurement of shrinkage and bursting strength

After resin treatment, a total of 18 (eighteen) samples were prepared from all fabrics, nine of which were for shrinkage testing and nine for bursting strength testing. All 18 samples were then subjected to conditioning on a flat surface for at least 24 hours before testing under standard atmospheric conditions at a relative humidity of 65% ± 2% and a temperature of 20 ± 2°C. Firstly, the lengthwise and widthwise shrinkage of the samples was calculated using equations (21) and (22) after washing the samples according to AATCC TM-135. The test sample with lengthwise and widthwise marking is shown in Figure 11.

Table 2: Experimental conditions for resin treatment

Parameters	Unit	Level		
Resin concentration	g/l	25	75	125
Softener concentration	g/l	15	45	75
Curing time	s	45	135	225

$$\text{Lengthwise shrinkage} = \frac{L_b - L_a}{L_b} \times 100 \quad (21)$$

$$\text{Widthwise shrinkage} = \frac{W_b - W_a}{W_b} \times 100 \quad (22)$$

where L_b represents length before washing, L_a represents length after washing (Figure 11), W_b represents width before washing and W_a represents width after washing (Figure 11).

Subsequently, the bursting strength (kPa) of each resin treated sample was measured using a pneumatic bursting tester with a specimen of 30 mm in diameter according to the ISO-139388-1 test method.

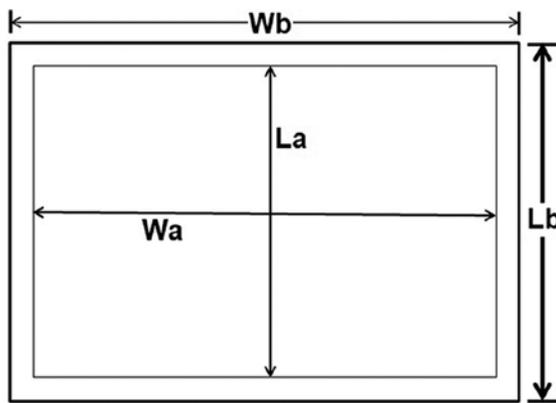


Figure 11: Test sample with lengthwise and widthwise marking

3 Results and discussion

3.1 Analysis of model performance

The graphical operations of developed fuzzy resin finishing models are depicted using the two examples in Figures 12 and 13. For a simple demonstration, out of nine rules only two fuzzy rules are explained here. According to Rule 4, if RC (resin concentration) is M, SC (softener concentration) is M and CT (curing time) is M, then outputs LS (lengthwise shrinkage) is L5 (Level 5), WS (widthwise shrinkage) is L5 (Level 5) and BS (bursting strength) is L5 (Level 5). Moreover, according to Rule 8, if RC is H, SC is H, and CT is M, then the outputs are as follows: LS is L9, WS is L1 and BS is L7. An example is given for Rule 4, where if input RC is 75 g/l, SC is 45 g/l and CT is 135 s, then then all nine fuzzy rules will be evaluated simultaneously to determine the fuzzy output of shrinkage and bursting strength. However, some of the rules will remain defunct as ‘fuzzy and’ function has been used in the antecedent part of the fuzzy rules and no output fuzzy set will be produced. The outputs of active fuzzy rules are then aggregated to arrive at a final output fuzzy set. Lastly, the Fuzzy-predicted outputs from the MATLAB’ fuzzy rule viewer were found to be LS is 4.15%, WS is 1.11% and BS is 294 kPa, as shown in Figure 12. Likewise, in the case of Rule 8, if input RC is 125 g/l, SC is 75 g/l and CT is 135 s, then predicted values are found to be LS is 6.5%, WS is 0.269% and BS is 306 kPa, as presented in Figure 13.

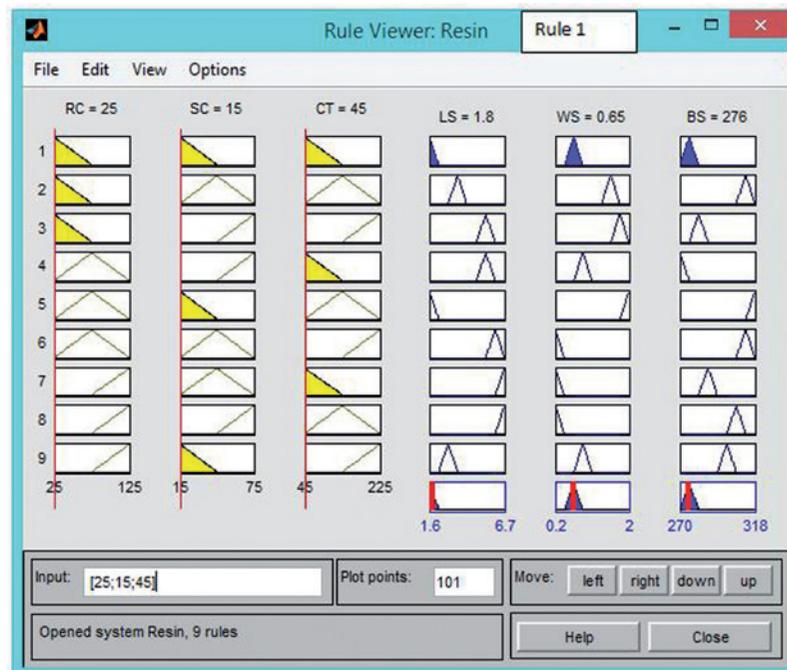


Figure 12: Graphical operation of the fuzzy expert system model (Rule 4)



Figure 13: Diagrammatic action of the fuzzy expert system (Rule 8)

3.2 Analysis of experimental results

3.2.1 Effect of resin concentration, softener concentration and curing time on fabric shrinkage

Figures 14 and 15 depict the effect of resin concentration, softener concentration and curing time on fabric shrinkage. It is clear from the figures that the slope of shrinkage (%) is non-linear with the effect of resin concentration, softener concentration and curing time. With an initial increase in resin concentration, the number of cross-links between the resin and free hydroxyl groups in the viscose cellulose chains quickly increases, resulting in a drastic decrease in fabric shrinkage. The shrinkage of viscose fabrics is mainly due to their ability to absorb more moisture because of the existence of hydroxyl groups in the cellulose. As the result of water absorption, the movement of cellulose polymer chains is also enabled in the amorphous regions by disrupting the internal hydrogen bonds between the cellulose chains. When the fabric is dried after wetting, the hydrogen bonds between the cellulose chains are reformed in new relaxed positions. With an increase in resin concentration, the hydroxyl groups of adjacent cellulose chains are cross-linked, thus making the fibres less inclined to water absorption and chain disturbances, resulting in a decrease in

fabric shrinkage. Nevertheless, further increases in resin concentration result in a gradual decrease in shrinkage. This is because the number of available free hydroxyl groups decreases in the viscose cellulosic fabric with initial cross-linking.

Moreover, it is evident from Figures 14 and 15 that the effect of softener concentration on fabric lengthwise and widthwise shrinkage control is non-linear, as well as less significant. Furthermore, at a lower resin concentration, the effect of increasing time is considerably significant in reducing fabric shrinkage due to effective resin cross-linking. However, a higher resin concentration slightly compensates for the reduced time, while shrinkage is reduced effectively, even when curing time is reduced.

3.2.2 Effect of resin concentration, softener concentration and curing time on fabric bursting strength

The effect of resin concentration, softener concentration and curing time on the fabric bursting strength is illustrated in Figure 16 (a–b). It is clear from Figure 16 (a) that an increase in resin concentration results in a decrease in fabric bursting strength. This may be attributed to several factors, including an increase in fibre brittleness, a decrease in yarn elongation and slippage properties, fabric stiffening or some cellulosic degradation during

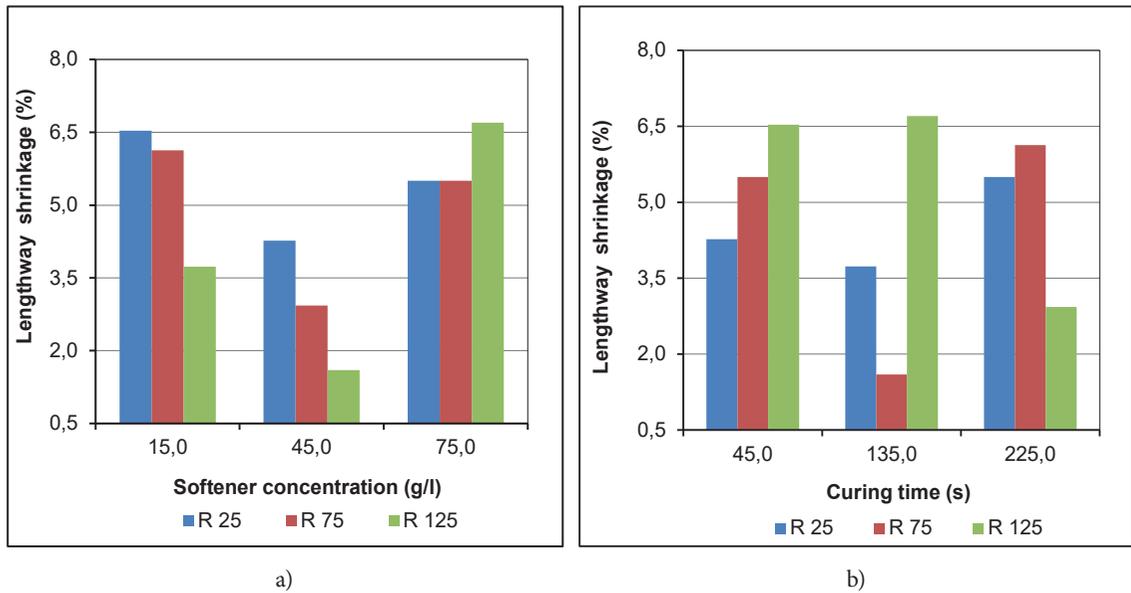


Figure 14: Effects on lengthwise shrinkage: a) resin and softener, and b) resin and curing time

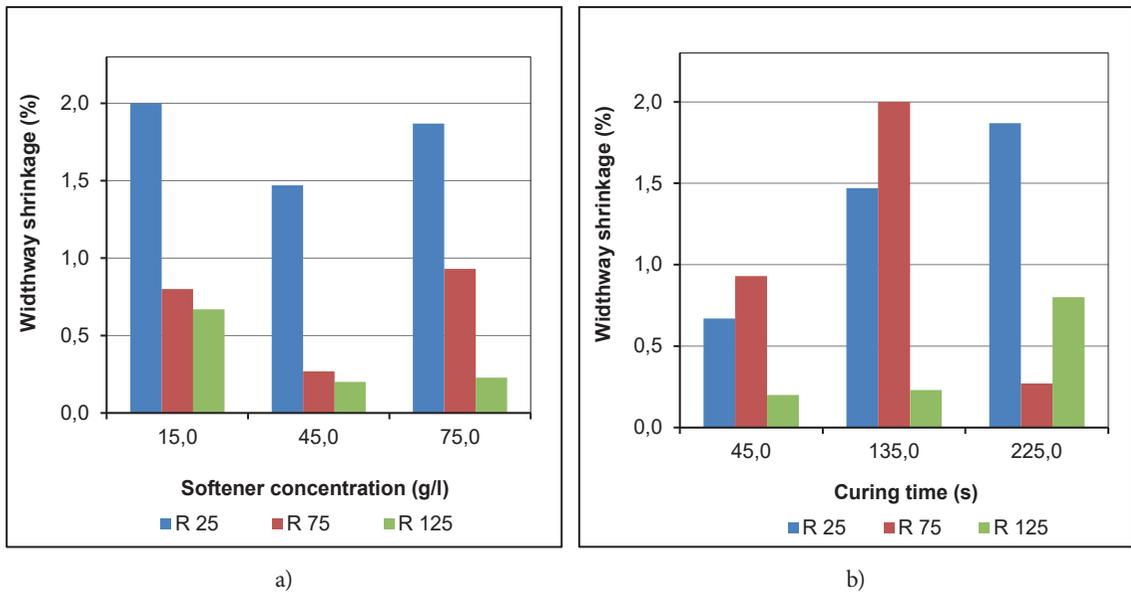


Figure 15: The effects on widthwise shrinkage: a) resin and softener, and b) resin and curing time

acidic resin finishing conditions. Likewise, the effect of resin concentration and curing time on the fabric bursting strength is shown in Figure 16 (b). It is evident from Figure 16 (b) that the effect of increasing curing time is more prominent at a lower resin concentration. However, at a higher resin concentration, there is a significant bursting strength loss, even at a reduced curing time. The addition of a softener results in an improvement in fabric bursting strength. This may be attributed to a decrease in fibre and yarn brittleness and stiffening,

and an increase in yarn slippage properties due to the use of a softener.

The effectiveness of increasing softener concentration to improve fabric bursting strength is better at a lower resin concentration but poor at a higher resin concentration. This is because any loss of fabric bursting strength due to stiffening and brittleness induced by the resin may be compensated for or recovered by the softener. However, any loss of fabric bursting strength that occurs due to cellulose degradation can not be recovered through the application of softeners.

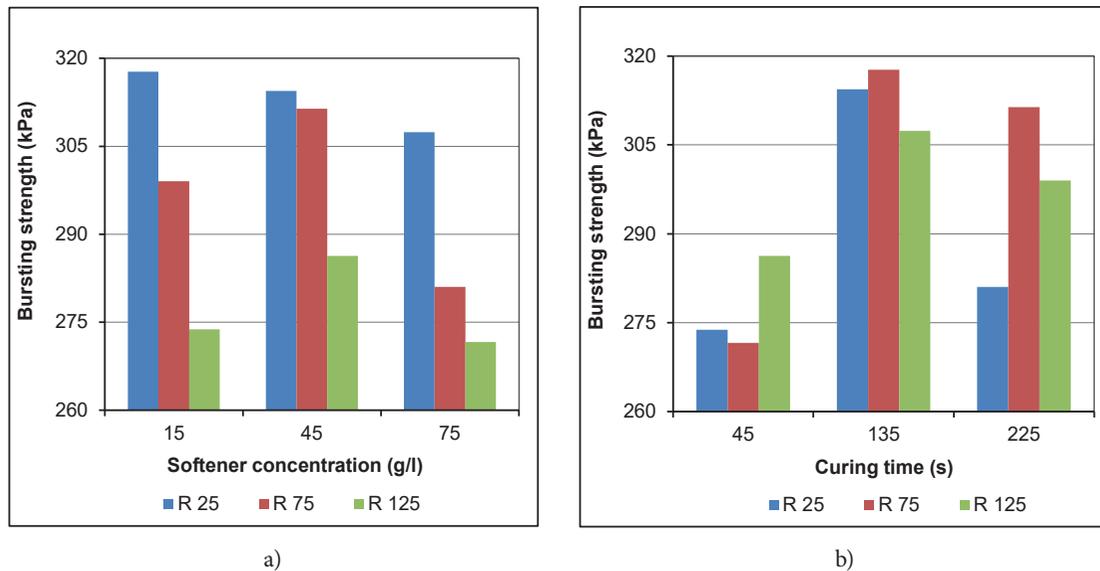


Figure 16: Effects on bursting strength: a) resin and softener, and b) resin and curing time

3.3 Validation of fuzzy resin model

The developed resin finishing model was validated using 9 (nine) sets of experimental data that were not used for the development of the proposed model. In fact, the fuzzy resin model was built based on the fuzzy expert knowledge and previous experience of the corresponding author. The corresponding author has more than 15 years of experience in the areas of production and R&D in the textile dyeing-finishing industry as a dye house general manager. The prediction was performed using the MATLAB® fuzzy rule viewer. The results from the developed fuzzy resin prediction model were then compared with

the experimental results. A comparison of predicted and experimental values of shrinkage and bursting strength of viscose plain knitted fabrics are shown in Table 3.

Further, the correlations between the predicted and experimental values of shrinkage and bursting under divergent resin finishing conditions are illustrated in Figures 17a, 17b, 17c. The mean absolute errors (MAE) between the predicted and experimental (actual) values of lengthwise shrinkage (LS), widthwise shrinkage (WS) and bursting strength (BS) were found to be 3.74%, 5.60% and 0.45%, respectively. In addition, the correlation coefficients (R) from

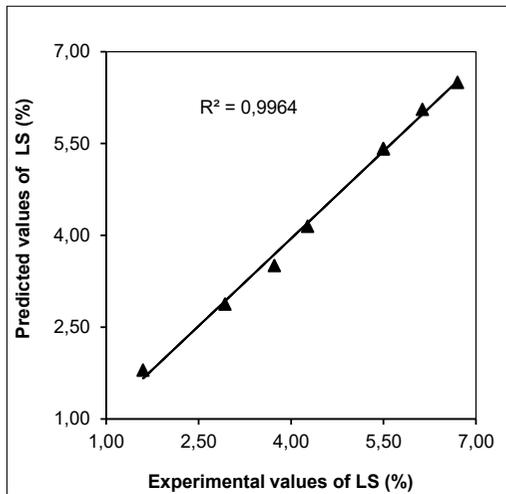
Table 3: Comparisons of predicted and experimental shrinkage and bursting strength

SL #.	Resin (g/l)	Softener (g/l)	Curing time (s)	Lengthwise shrinkage			Widthwise shrinkage			Bursting strength		
				Ev	Pv	AE (%)	E _v	P _v	AE (%)	E _v	P _v	AE (%)
1	25	15	45	-1.90	1.8	2.81	0.67	0.65	2.99	273.80	276	0.80
2	25	45	135	-3.73	3.51	5.9	1.47	1.55	5.44	314.40	312	0.76
3	25	75	225	-5.50	5.42	1.45	1.87	1.78	4.81	281.00	282	0.36
4	75	75	45	-5.50	5.42	1.45	0.93	0.88	5.91	271.60	272	0.15
5	75	15	135	-1.60	1.8	12.5	2.00	1.93	3.50	317.70	316	0.54
6	75	45	225	-6.13	6.06	1.14	0.27	0.269	0.37	311.40	312	0.19
8	125	75	135	-6.70	6.5	2.99	0.23	0.26	13.04	307.40	306	0.46
9	125	15	225	-2.93	2.88	1.71	0.80	0.87	8.75	299.00	300	0.33
Mean Absolute Error (%)				3.74			5.60			0.45		
Co-efficient of determination (R^2)				0.996			0.992			0.996		

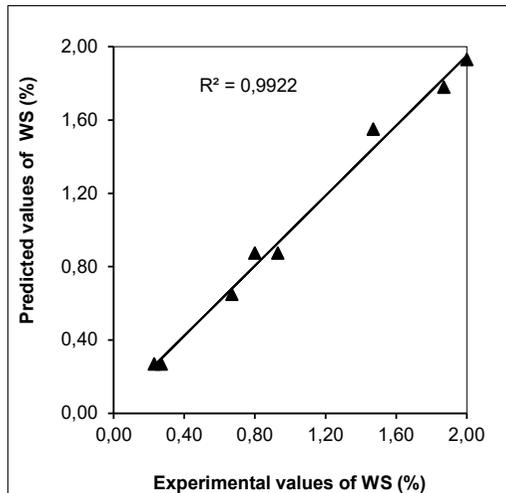
E_v = experimental value; P_v = predicted value; AE = absolute error

the predicted and experimental values of LS, WS and BS were found to be 0.998 ($R^2 = 0.996$), 0.992 ($R^2 = 0.992$) and 0.998 ($R^2 = 0.996$), respectively, and elucidated the good agreement by the developed FES resin model.

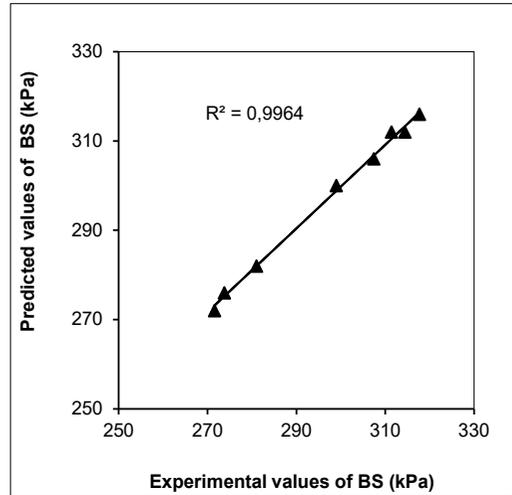
Additionally, it is evident from Table 3 that all the results of R^2 and MAE (%) are very close to each other, which indicates the ability and accuracy of the fuzzy resin model to predict the shrinkage control and bursting strength of viscose plain knitted fabrics. It can be decisively stated that the model developed in this study can perform effectively with good prediction accuracy in a non-linear complex field. From Table 3, the optimal parameters in the resin-finishing process were found to be a resin concentration of 75 g/l, a softener concentration of 45 g/l and a curing time of 225 seconds, as the best shrinkage control with the desired fabric bursting strength.



a)



b)



c)

Figure 17: Correlation between a) experimental and predicted values of lengthwise shrinkage, b) experimental and predicted values of widthwise shrinkage, and c) experimental and predicted values of fabrics bursting strength

4 Conclusion

It was found from our experimental study that the shrinkage of fabric is significantly reduced by increasing the resin concentration and curing time, accompanied by a severe loss in the fabric bursting strength. However, such loss of fabric bursting strength can be improved by increasing softener concentration with some loss in shrinkage control. Moreover, there was a significant interaction between the resin concentration and curing time, and between the resin and softener concentrations. It is obvious that the effects of resin concentration, softener concentration and curing time on shrinkage control are not linear. The FES resin model in this regard is found to be extremely effective in a non-linear domain for determining the optimal resin finishing conditions for best shrinkage control with a minimum loss in fabric bursting strength. The optimal parameters in the resin-finishing process were identified as a resin concentration of 75 g/l, a softener concentration 45 g/l and a curing time 225 seconds. In the current study, the FES resin model was developed by taking resin concentration, softener concentration and curing time as input variables to predict the shrinkage and bursting strength of viscose plain knitted fabric. The fuzzy resin model derived in this research was confirmed by experiment data. The mean absolute

errors between the experimental values of lengthwise shrinkage (LS), widthwise shrinkage (WS) and bursting strength (BS) and those predicted by the FES resin model were found to be 3.74%, 5.60% and 0.45%, respectively. Likewise, the coefficients of determination (R^2) from the experimental and predicted values of LS , WS and BS were found to be 0.996 and 0.992 and 0.996, respectively. The results indicate the brilliant prediction performance of the developed fuzzy resin model. It can thus be decisively concluded that the fuzzy model built in this study can be applied in the textile and dyeing industries for selecting significant process parameters and their required levels to achieve a targeted level of product quality. Conversely, without such a model, a production engineer must conduct numerous trials based on assumptions to achieve the target product quality.

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