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Optimizing the impact resistance of high tenacity Nylon 66 weft knitted fabrics via genetic algorithm

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Abstract

The aim of the present research is evaluating the impact resistance of weft knitted fabrics which are knitted in basic patterns from the high tenacity Nylon 66. The woven fabrics have been applied for manufacturing technical and ballistic textiles so far. Although woven fabrics have been demonstrated satisfactory tensile properties, but they have not been resisted against impact, because of their poor strain against tensile forces. This research is important because knitted fabrics are applied in wide range of applications including technical textiles such as, package belts, safety belts, ballistic belts, and can be used to remove ice from airplane wings. Various knitted fabrics with different knitting elements such as knit, tuck and miss loops were produced. Mechanical properties including strength, work of the rupture and impact resistance of knitted samples were tested. The artificial neural network was used to predict mechanical properties of fabrics produced from the knitted structure as fitness function in genetic algorithm. After that, genetic algorithm was applied to find the optimum structure of knitted fabric with maximum impact resistance. The results of the genetic algorithm show that optimum structure of the fabric is cross-miss and rib structure with high stitch density.

Keywords: Knitted fabric, Optimizing, Impact resistance, High tenacity, Genetic algorithm

Introduction

When a missile hits a fabric, a reflective force is implied to the missile which reduces its speed and at times fabric is deformed and strain waves are transferred to fabric edges through the yarns. Kinetic energy of missile is dissipated by strain energy of yarns in places where slipping friction exists. Thus, missile energy dissipation is influenced by factors such as; fiber type, fabric structure, missile geometry, speed of impact, friction between missile and fabric and friction of yarns and fibers in the fabric. Determining a quantitative value for yarn strain energy, kinetic energy and energy dissipation in places with friction is very difficult and in some cases impossible (Duana et al. 2006a).

Impact loads are dynamic indentation loads. Mass and speed of missile are the two determining factors of impact force. Impact energy is divided into two elements of absorbed energy by surface and elastic energy which causes missile to turn back. A great number of experiments and theoretical efforts has been conducted in order to investigate the behavior of impact on yarn and fabrics. Transverse impact behavior is investigated on one layer fabrics (Roylance 1977). In some researches, ballistic impacts on systems containing fabrics, have been studied (Field and Sun 1990; Wilde et al. 1973; Wilde 1974; Briscoe and Motamedi 1992; Shim et al. 1995; Shocky et al. 2011). In a fabric system under ballistic impact, parameters like fiber characteristics, weave pattern and its type, number of fabric layers, surface density, missile parameters and impact parameters affect system energy absorption (Cunniff 1992). Surface friction also plays an important role in ballistic impact systems which affects energy absorption capacity (Bazhenov 1997).

Generally, only primary and secondary speeds in ballistic experiments are measured which are the entering and exiting speed of bullet when it passes through the aim, respectively. However, an improved laser system is devised to measure missile speed in ballistic impact experiments (Starratt et al. 2000). A large quantity of studies have been conducted on ballistic impacts of high tensile strength fabrics (Cunniff 1992; Bazhenov 1997; Starratt et al. 2000; Tan et al. 2003; Cheeseman and Bogetti 2003; Duana et al. 2005, 2006b; Nilakantan et al. 2010; Parga-Landa and Hernandez-Olivares 1995; Billon and Robinson 2001; Zheng et al. 2006; Nilakantan et al. 2011). The effects of friction have been studies on ballistic impact behavior on high tensile strength fabrics (Duana et al. 2005, 2006a). Likewise, fabric armor behavior against ballistic impacts has been modeled (Billon and Robinson 2001; Tan and Ching 2006). Regarding broad usage of woven fabrics in armor systems and also yarn arrangement in these fabrics, the crimp in woven fabrics against ballistic impacts has been also modeled (Tan et al. 2005). Studies have been conducted on ballistic impact modeling on armor fabrics in which textile based composites play an important role (Novotny et al. 2007; Mamivand and Liaghat 2010; Lim et al. 2003; Barauskas and Abraitiene 2007).

Although woven fabrics have been demonstrated satisfactory tensile properties, but they have not been resisted against impact, because of their poor strain against tensile forces. Therefore, in this work, effect of impact has been studied on different weft knitted fabrics. Mechanical properties of knitted samples were tested. The artificial neural network was applied to predict mechanical properties of fabrics from weft knitted fabric factors in the knitting process. Genetic algorithm was then applied to find the optimum structure of knitted fabric with optimum impact resistance.

Methods

Materials

In order to investigate the tensile strength of various fabrics, 100-denier 20-TPM multifilament Nylon 66 yarns, were used and four knitting patterns with two different densities were produced by Falmac single knit circular knitting machine (48 feeders, gauge 24) and Mayer & Cie double knit circular knitting machine (96 feeders, gauge 24).

Mechanical properties

Tensile strength and work of rupture of samples with dimensions of 200 × 20 mm were measured in the course and wale direction by Zwick Matrialprufung Materi 1446 according to ASTM D5034-09 (ASTM 2013). The impact resistance of the samples was measured by Charpy impact test by Wolpert PW30/15 K charpy tester based on ISO

179-1:2000 (ISO 2000). The pendulum had energy of 150 J and the specimens were prepared in 150 × 50 mm. Impact surface was 50 × 2 mm and the pendulum hit the center of the sample. The samples were clamped in two sides.

Artificial intelligence

Five samples were used for testing every type of fabrics and the results were used as neural network inputs and outputs. In the neural network, input parameters were knit ratio that is the ratio of knitted loops in comparison with total loop in each unit cell of knitted structure, miss ratio that is the ratio of missed loops in comparison with total loop in each unit cell of knitted structure, stitch density and loop length. Output parameters were the work of the rapture in the course and wale direction, the tensile strength in the course and wale direction and impact resistance. Figure 1 shows the knitting notation of the different patterns.

An artificial neural network with four nodes in the input layer, seven nodes in the hidden layer and five nodes in the output layer was used. Levenberg–Marquardt Back Propagation training algorithm with mean square error performance was used to train the network. Figure 2 shows the structure of artificial neural network.

The learning rate of neural network was 0.01, the momentum was 0.5, maximum epoch number was 500 and the final value of performance function was 10^{-2}. Linear transfer function, log-sigmoid transfer function and hyperbolic tangent sigmoid function, were used for input layer, hidden layer and output layer, respectively. 70 % of data were used for training, 10 % for validation and 20 % for testing. The initial size of population in genetic algorithm that was used to optimized structure, was 20. The chromosome structure is depicted in Fig. 3.

In order for a better performance it is inevitable that mechanical parameters should tend to maximum value. Thus, the fitness function is defined as reverse value of

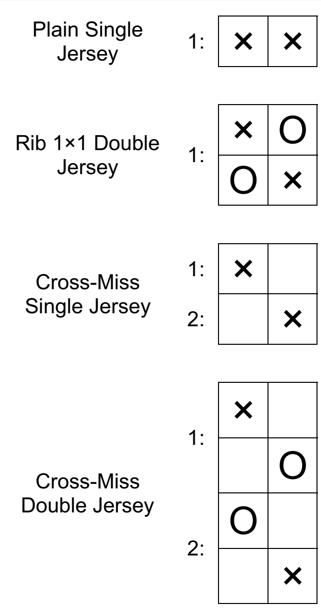

Fig. 1 The knitting notation of the different patterns. *Cross* front needle knit, *circle* back needle knit, *blank* miss knit

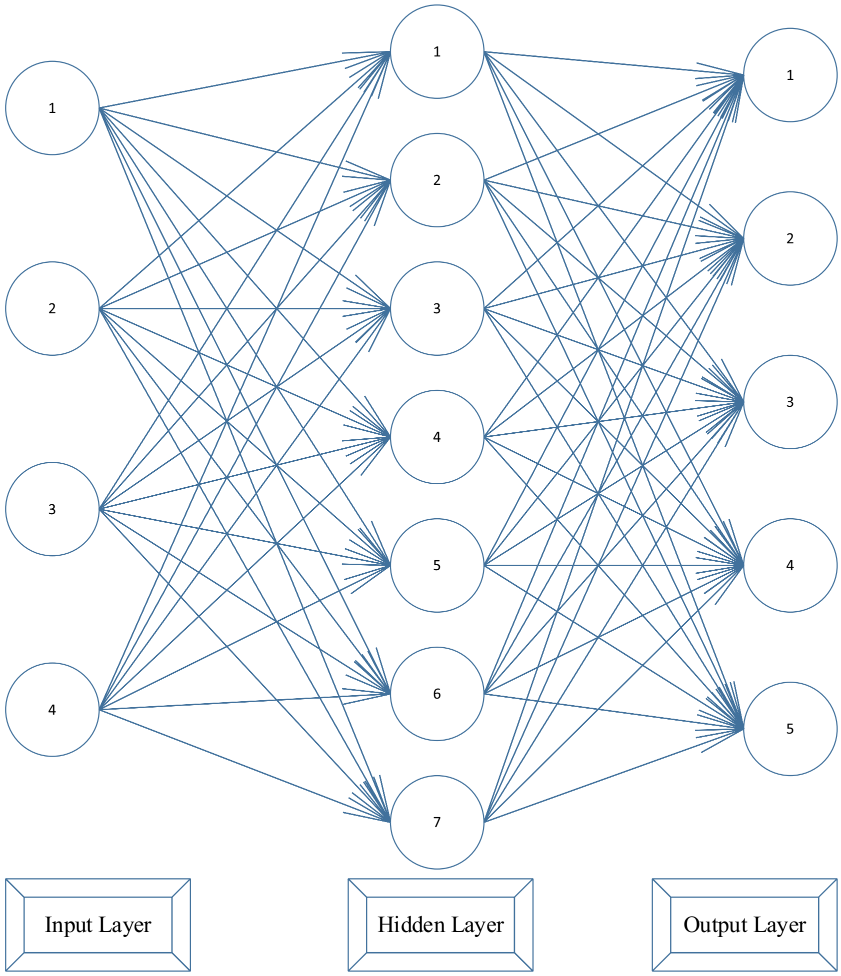

Fig. 2 The structure of neural network

Knit Ratio	Miss Ratio	Stitch Density	Loop Length

Fig. 3 Chromosome structure

mechanical properties. Generally, the number of individuals remained constant in each generation and the best surviving ones and the ones with lower fitness value were eliminated in each generation. In the chromosome producing, the first and the second genes which were related to knit ratio and miss ratio, got a value of two totally. Therefore, for double jersey fabrics with 100 % knit, two was considered for the first gene and zero for the second gene. Consequently, for single jersey fabrics with 100 % knit, one and zero were considered for the first and the second genes correspondingly.

The next generation was made from the previous generation. For this, one member as elite member was transferred to the next generation directly and crossover for the other members was considered 0.9. The rest of individuals of the next generation were formed by mutation.

For determining fitness function, artificial neural network output was used. Therefore, each individual input was added to the trained neural network. Eventually, the output values of network for each output parameter was reversed and their summation was considered as fitness value of the mentioned individuals. After several generations, when fitness function value was not changed or reached desired fitness value, the genetic algorithm was stopped and the last generation was shown as the optimized population whereof the optimized knitting parameters values could be extracted by the use of gene structure. Figure 4 shows optimization procedure schematically.

Results and discussion

The mechanical properties of 40 samples from 8 different types of fabrics were tested at first. Table 2 shows the results of mechanical tests. After determining knitting parameters which are shown in Table 1, they were used as neural network inputs and results of tensile strength, work of rupture and impact resistance were used as target of neural network.

One can see from Table 2 that RDH sample has the highest work of rupture and tensile strength in wale direction, and impact resistance and CDH sample has the highest tensile strength and work of rupture in coarse direction.

A trained artificial neural network with four nodes in the input layer, seven nodes in the hidden layer and five nodes in the output layer was used as fitness function. Figure 5 shows network performance values and Fig. 6 shows predicted values versus target values, which has an acceptable correlation coefficient.

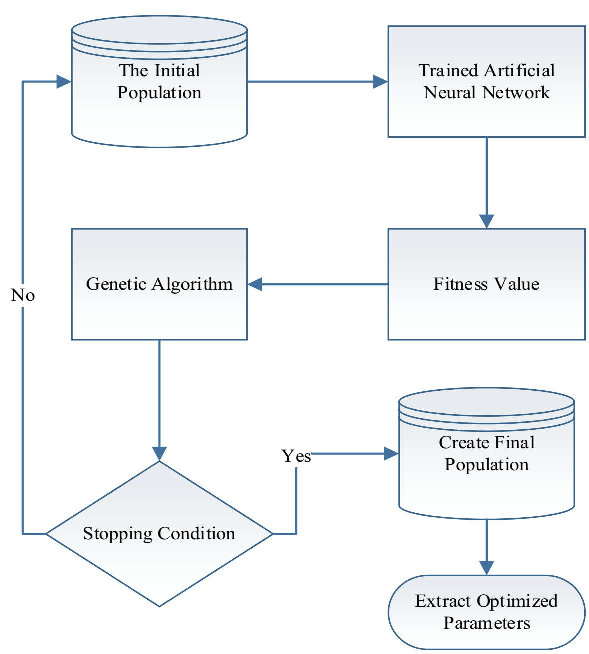

Fig. 4 Schematic of optimizing procedure

Table 1 Fabrics properties

Sample code	Structure	CPC	WPC	Weight (g/m^2)	Stitch density ($1/cm^2$)	Loop length (mm)
PSL	Plain, Single Jersey, Low Density	11.46	10.56	55	121	3.9
PSH	Plain, Single Jersey, High Density	15.36	14.13	68	217	2.9
RDL	Rib, Double Jersey, Low Density	13.35	21.12	105	282	2.6
RDH	Rib, Double Jersey, High Density	14.93	21.56	116	322	2.4
CSL	Cross Miss, Single Jersey, Low Density	14.59	12.34	84	180	3.3
CSH	Cross Miss, Single Jersey, High Density	17.05	14.48	102	247	2.8
CDL	Cross Miss, Double Jersey, Low Density	12.2	19.84	105	242	2.8
CDH	Cross Miss, Double Jersey, High Density	14.44	23.54	156	340	2.3

Table 2 The results of mechanical tests

Sample code	Tensile strength (N)		Work of rupture (N m)		Impact resistance (KJ)
	Course direction	Wale direction	Course direction	Wale direction	
PSL	54	89	2.23	2.27	4.6
	55	91	2.41	2.7	4.8
	51	90	2.13	2.49	4.7
	56	95	2.52	2.9	5.2
	54	92	2.38	2.79	4.8
Average	54	91.4	2.334	2.63	4.82
SD	1.871	2.302	0.154	0.251	0.228
cv%	3.464	2.519	6.600	9.555	4.731
PSH	66	120	2.9	3.65	7
	72	127	3.16	3.82	7.3
	68	123	3	3.78	7.1
	69	121	3.09	3.7	7.1
	67	122	2.99	3.76	7.1
Average	68.4	122.6	3.028	3.742	7.12
SD	2.302	2.702	0.100	0.067	0.110
cv%	3.366	2.204	3.298	1.797	1.539
RDL	59	261	2.73	7.24	14.2
	57	258	2.56	7.1	14.1
	58	260	2.67	7.18	14.1
	60	272	2.8	7.37	14.8
	56	249	2.41	6.93	13.5
Average	58	260	2.634	7.164	14.14
SD	1.581	8.216	0.153	0.164	0.462
cv%	2.726	3.160	5.811	2.286	3.264
RDH	60	269	2.8	7.33	15.2
	62	274	2.86	7.42	15.6
	59	268	2.73	7.29	14.7
	63	281	2.9	7.73	15.8
	61	271	2.81	7.36	15.3
Average	61	272.6	2.82	7.426	15.32
SD	1.581	5.225	0.064	0.176	0.421
cv%	2.592	1.917	2.284	2.376	2.746

Table 2 continued

Sample code	Tensile strength (N)		Work of rupture (N m)		Impact resistance (KJ)
	Course direction	Wale direction	Course direction	Wale direction	
CSL	109	102	3.9	2.94	5.9
	111	106	3.96	2.99	6.1
	115	108	4	3.05	6.2
	120	110	4.2	3.12	6.5
	116	109	4.07	3.09	6.4
Average	114.2	107	4.026	3.038	6.22
SD	4.324	3.162	0.115	0.073	0.239
cv%	3.787	2.955	2.862	2.412	3.838
CSH	113	123	3.99	4.24	7.5
	120	132	4.23	4.31	8.4
	112	119	3.98	4.16	7.3
	118	127	4.1	4.46	8
	115	125	4.01	4.3	7.9
Average	115.6	125.2	4.062	4.294	7.82
SD	3.362	4.817	0.105	0.110	0.432
cv%	2.908	3.847	2.590	2.570	5.530
CDL	109	187	4.78	5.42	9.5
	106	183	4.73	5.39	9
	110	192	4.8	5.52	10.1
	112	195	4.86	5.6	10.8
	108	191	4.79	5.49	9.8
Average	109	189.6	4.792	5.484	9.84
SD	2.236	4.669	0.047	0.083	0.673
cv%	2.051	2.463	0.972	1.518	6.840
CDH	127	206	6.19	6.24	13.6
	124	201	6.08	6	13.3
	128	215	6.22	6.39	13.8
	132	220	6.32	6.61	14.1
	126	212	6.11	6.35	13.5
Average	127.4	210.8	6.184	6.318	13.66
SD	2.966	7.463	0.095	0.223	0.305
cv%	2.328	3.540	1.537	3.528	2.232

In optimization by genetic algorithm, chromosomes with four genes and the primary population with 10 individuals were used. In each generation the mean fitness values and the best fitness values were calculated. After 20 generations, the gene values of the best individual of the last generation were considered as the values of optimized parameters. Figure 7 shows the fitness values for all generations in one run. Table 3 shows the results of genetic algorithm output for 20 times running of the algorithm.

Double jersey fabrics have more strength and impact resistance as appose to single jersey ones. Since loops can stretch after the impact, increasing knit ratio causes more energy waste in loops. Consequently, by increasing loop density work of rupture increases. As a result, it is expected to observe more impact resistance in high density double jersey fabrics. As it can be seen from Table 3 and Fig. 8, the results are in a good compliance with reality.

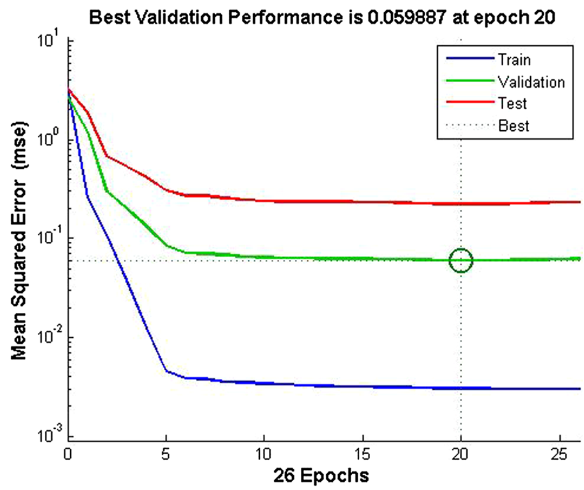

Fig. 5 Network performance

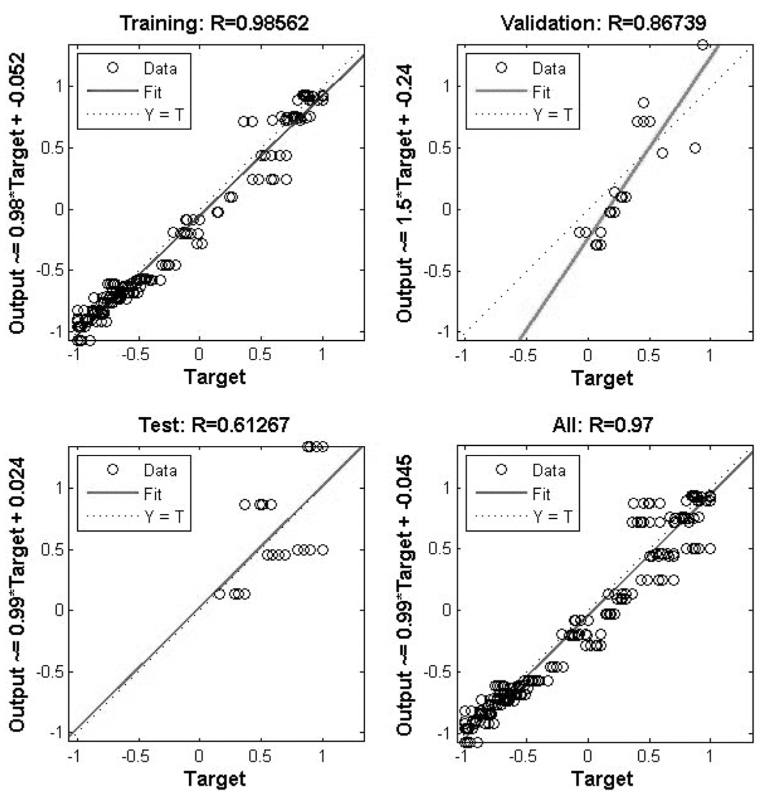

Fig. 6 Predicted values versus target values

Conclusion

Properties of weft knitted fabrics were determined by yarn properties, fabric structure and any mechanical and chemical process which were performed about fabric and yarn. Since weft knitted fabrics have various behaviors in the course and the wale directions, mechanical tests were carried out in the above mentioned directions.

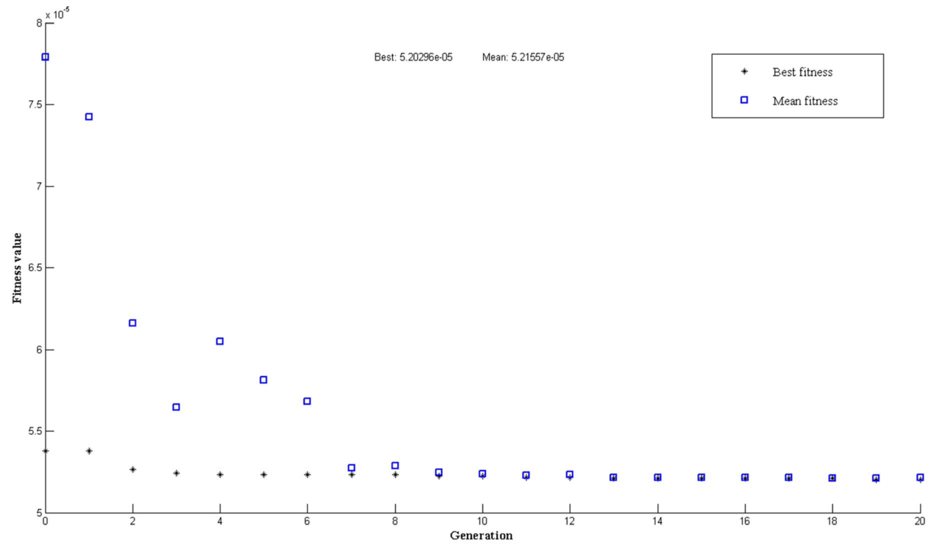

Fig. 7 The fitness values

Table 3 The results of genetic algorithm

Run	Genes			
	Knit ratio	Miss ratio	Stitch density	Loop length
1	1.878	0.122	302	2.508
2	1.892	0.108	332	2.392
3	1.804	0.196	340	2.363
4	1.957	0.043	294	2.542
5	1.996	0.004	338	2.370
6	1.988	0.012	314	2.459
7	1.907	0.093	337	2.374
8	1.976	0.024	293	2.546
9	1.978	0.022	283	2.591
10	1.670	0.330	287	2.572
11	1.906	0.094	318	2.444
12	1.632	0.368	296	2.533
13	1.832	0.168	298	2.525
14	2.000	0.000	322	2.429
15	1.800	0.200	295	2.537
16	1.998	0.002	315	2.455
17	1.997	0.003	313	2.463
18	1.992	0.008	310	2.475
19	1.974	0.026	304	2.500
20	1.948	0.052	319	2.440
Average values	1.90625	0.09375	310.5	2.47642

For Double Jersey Cross Miss, the work of rupture and the tensile strength in course direction were maximum. Work of rupture and tensile strength in wale direction and impact resistance were maximum for Rib patterns. As for impact resistance, double jersey patterns and high stitch density fabrics showed better results as appose to single jersey and low stitch density fabrics correspondingly.

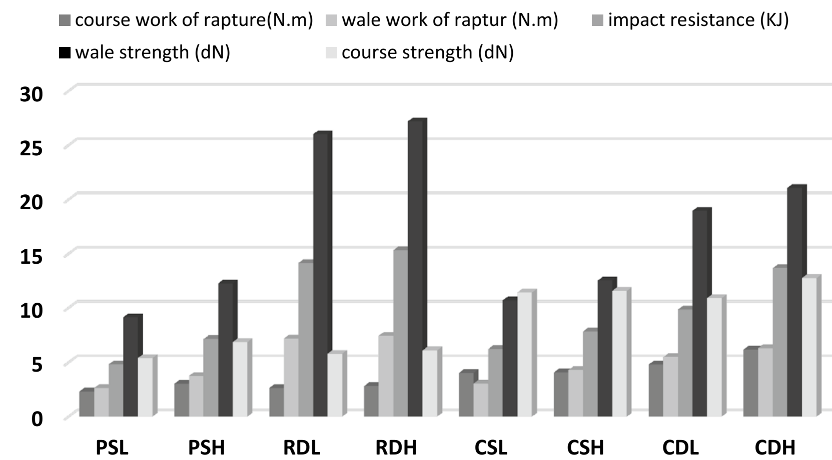

Fig. 8 Average of mechanical properties

It is concluded that, fabrics with very high knit ratio, low miss ratio, high stitch density and short loop length, have the most optimized impact resistance, tensile strength and work of rupture in both course and wale direction.

In general, high stitch density Rib showed better impact resistance and had better tensile strength and work of rupture in both directions as appose to other patterns which is in compliance with the results driven from genetic algorithm prediction.

Authors' contributions

FH carried out the experiments and rounded up data. DS supervised the whole process. MH and FH developed the literature review, coded. MH and DS conducted genetic algorithm and neural network. PRT guided the analysis of the results and conclusions and contributed to the formatting and editing of the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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