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EVALUATION OF THE RELATIONSHIP BETWEEN ELASTIC AND ELECTRICAL CHARACTERISTICS OF CONDUCTIVE TEXTILES

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Abstract: *Smart textiles are fabrics that interact intelligently with nearby surroundings or consumers. The electronic textile (e-textile) can sense environmental circumstances or stimuli and provide information that can effectively respond to and adapt actions. An electrically conductive textile is a piece of smart textile that incorporates conductive fibres, yarns, fabrics, and ultimate products. Conductivity is one of the properties that allow the integration of textiles in electrical circuits to ensure the functionality of electronic devices. The integration of conductive yarns in a structure is a complex and seldom a uniform process as it needs to be ensured that the electrically conductive fabric is comfortable to wear or soft to touch rather than hard and rigid. The paper presents an original method for determining the relationship between the conductivity of conductive textile structures and their elastic characteristics. Statex and Bekinox conductive yarns of fineness 296-610 dtex were used to make woven and knitted structures. The SEM and EDAX analyses of the wires were carried out on the Scanning microscope Quanta FEI 200. The physical-mechanical characteristics analyzed highlighted: strength (N) and elongation at break (%), tear resistance (N), resistance to deformation (kPa) and deformation (mm) of the conductive structures. The modulus of elasticity (N/cm^2) and anisotropy was calculated. The correlation coefficients between the three variables have high values (>0.980). The Lloyd material testing equipment coupled with a data acquisition unit-DAQ (white box) was used for the simultaneous variation of elasticity and electrical conductivity of textile structures.*

Keywords: *textile, conductivity, elasticity, deformation, correlation*

1. INTRODUCTION

Conductive yarns and fabrics are specialized textile materials that are made by incorporating conductive materials such as metals, carbon nanotubes, or conductive polymers into their structure [1]. These materials have the ability to conduct electricity and can be used in a wide range of applications such as wearable technology [2, 3], smart textiles [4], electromagnetic shielding [5] and electronic devices [6]. Conductive materials are being increasingly used in specialized clothing to create high-performance garments that are both comfortable and functional, allowing the garment to interact with its environment and enhance its capabilities [7]. Conductive fabrics can undergo mechanical deformation, which can affect their electrical properties. Mechanical deformation refers to the change in shape or size of the fabric due to external forces, such as stretching, compression, bending, or twisting. When conductive fabrics are subjected to mechanical deformation, their electrical resistance can change [8]. This is because the deformation can cause the conductive fibres/yarns in the fabric to move or reorient, which can change the path of the electrical current flowing through the fabric. As a result, the electrical conductivity of the fabric can either increase or decrease, depending on the nature and extent of the deformation. Stretching a conductive fabric can cause the component yarns and fibres to align in the direction of the stretch, which can increase the conductivity of the fabric along that direction [9]. On the other hand, compressing or twisting the fabric can cause the fibres to become more compacted, which can decrease the conductivity of the fabric. Understanding the mechanical behaviour of conductive fabrics is important for designing and engineering wearable electronics and smart textiles, where the fabrics are often subjected to a range of mechanical deformations during use. By characterizing the electrical response of conductive fabrics to different types and levels of mechanical deformation, designers can optimize the performance and reliability of their products. In general, conductive fabrics can have two types of stretching properties: mechanical stretching (the ability of the fabric to stretch and deform under mechanical stress, such as when it is pulled or bent) and electrical stretching (the ability of the fabric to change its electrical properties when it is stretched) [10]. The stretchable properties of conductive fabrics can vary depending on the specific material, composition, and manufacturing process. Several studies have investigated the effect of mechanical deformation on the electrical properties of conductive fabrics. A study found that stretching a conductive fabric along one direction increased its conductivity along that direction while reducing it perpendicular to the stretch. Another study examined the effect of bending on the electrical properties of conductive fabric. However, the extent of the change varied depending on the direction and degree of bending, suggesting that the behaviour of conductive fabrics under mechanical deformation is complex and highly dependent on specific conditions [11]. The paper presents an original method for determining the relationship between the conductivity of conductive textile structures and their elastic properties. The electrical resistance is stable for up to 40% strain, especially for the woven fabric sample, compared to the knitted fabric samples.

2. MATERIALS AND METHODS

The conductive yarns and the textile yarns Statex (Ag/PA)-Cotton-610 dtex, Statex (Ag/PA) -PES- 610 dtex and Bekinox-PES-400 dtex were used to obtain conductive fabric structures. Classic/conventional technologies of weaving and knitting were applied to provide two variants of knitted structures (A4-jerse, C5-interlock and C6 patent) and a variant of woven structures (B4-plain). The physical-mechanical characteristics of the analyzed textile structures highlighted: resistance (N) and elongation at break (%), resistance to tearing (N), resistance to deformation (kPa) and deformation, and resistance to tearing (N). The SEM and EDS analyses of the yarns were carried out on the Auriga model workstation produced by Carl Zeiss SMT Germany FESEM FIB with field emission source with Gemini column for the electron beam that highlighted the arrangement of the component elements of the conductive yarns and the elemental analysis. The modulus of elasticity was calculated knowing the initial length (L) of the tensile test specimen, the applied force (N) and the elongation (%) at the transition point from the elastic zone to the plastic zone of the stress-elongation curve, the difference in length (ΔL), the thickness of the textile structures (mm), the area of the sample (cm^2). The ratio between the modulus of elasticity in the horizontal and vertical direction allowed for obtaining the anisotropy of the textile structures. The Solidwork program highlighted the contribution of conductive structures to stress. The correlation coefficients between the three variables were calculated. The Lloyd material testing equipment coupled with a data acquisition unit-DAQ (white box) was used for the simultaneous determination of the variation of strain and resistance of textile structures highlighted. A conductive fabric sample of 5cm by 20cm clamped between the jaws of a Llyod tensile machine set at gauge length 20. The fabric sample is also connected to the DAQ unit that continuously measures the electrical resistance of the fabric. The samples' cycling (loading and offloading) was performed at a 200 mm/min cycling speed. For a complete cycle, the fabric is loaded continuously to a specified per period for 2 seconds (relaxation) and then released centage releasing the load at the same speed as the gauge length. The strain was applied at 5%, 10% 15% 20% 30%, 40%, and 50%. Each sample was tested for 5 cycles, meaning loading and offloading 5 times. The first cycle was always strange for all the tests because the sample underwent a kind of pretension in the first cycle, thus the correct measurements always start in the second cycle.

3. RESULTS

Table 1 shows the main characteristics of the conductive yarns used to make textile structures and Fig.1 aspects of the longitudinal sections of the conductive yarns and the EDS diagrams that highlight the main compositional elements. The main characteristics of woven and knitted structures are presented in Table 2.

Table 1: Conductive yarns characteristics

No.crt.	Conductive yarn	Fineness, dtex	The apparent diameter, μm	Linear electrical resistance, Ω/m
1	Statex Ag/PA	610	284	76
2	Statex Ag/PA	296	228	220
3	Bekinox	Nm 50/2 (200 x 2 dtex)	273	2200

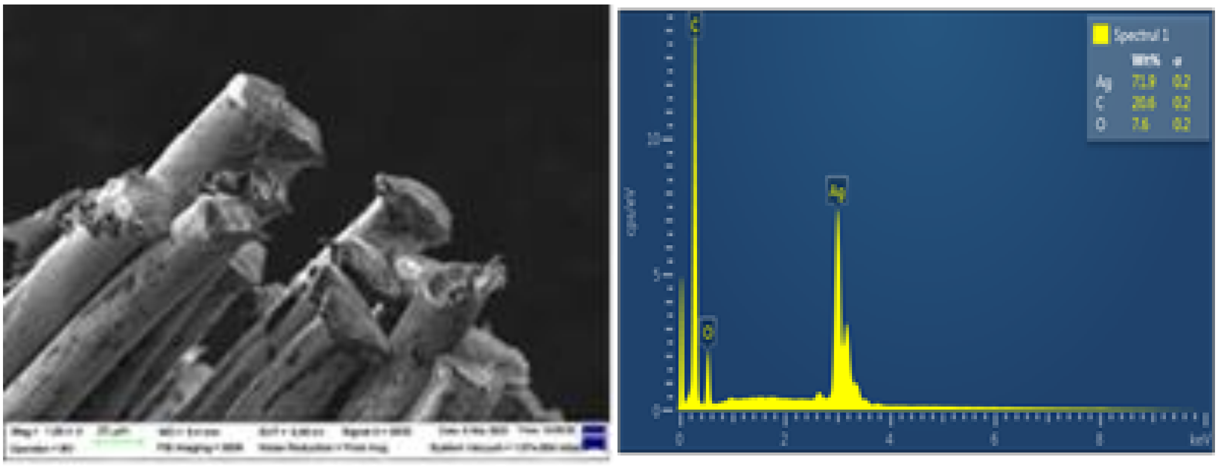
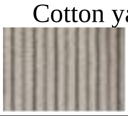


Fig. 1: SEM/EDS of a conductive yarn

Table 2: Conductive fabrics characteristics

Characteristics/Variant		Knit A4-jerse	Knit C5-interlock	Woven B4-plain	Knit C6 - patent
Mass/g/m^2		369,5	115	146	98,0
Length of metal yarn, cm/10cm		34	35	10,3	29,0
Yarn density, no./10cm	H	180	75	280	70
	V	48 Metallic yarns	40 Metallic yarns	44 Metallic yarns	46 Metallic yarns
		192 Cotton yarns 	50 Cotton yarns 	105 Cotton yarns 	90 Metalic yarn 
Breaking strength, N	H	617,8	431,54	1659,25	163,05
	V	539,8	234,40	764,69	197,73
Elongation at break,%	H	87,6	94,14	36,28	124,91
	V	113,3	171,64	22,28	92,89
Thickness, mm		1,57	0,96	0,49	0,56
Resistance to deformation	KPa	531,8	303,1	647,95	191,0
	mm	41,23	36,7	36,75	44,9
Tear resistance, N	O (Wa)	36,84	31,86	78,51	30,33
	V (Wf)	23,7	55,68	98,97	33,58

By applying its own procedure (INCDTP) the length of the conductive yarn, cm of yarn/10 cm of fabric in the textile structures was obtained and it varies from 10.3 cm/10 cm (B4) to 35 cm/110 cm (C5). The breaking force for knitted structure varies within the limits 163,5N (C6) – 617,8N (H) and 197,73N (C6)-539,8N (A4). The highest value of the elongations at the break on the horizontal direction is presented by C6 (124,91N) and for the vertical direction by C5 -171,64N. The woven structure (B4) is stronger than knitted structures (both directions) it has smaller elongation values. The knitted fabric with patent structure (C6) has the lowest resistance to deformation (191KPa) compared to the one with jerse structure (A4-531.8KPa) and interlock (C5-303 KPa). The higher density of the metal yarns but also the difference in the structure determines the high deformation of the A4 (41,23mm) and C6 (44,9mm) knitted variants compared to C5. The woven structures (B4) have the lowest value of the metallic yarn length, but the specific structure leads to a higher resistance of deformation (647,95) N against knitted structures and the lowest deformation (36,70mm). The Solidwork program was used to visualize the behaviour of the textile structures in the tensile strength test (Tinius Olsen dynamometer) (Fig.2). The increase in the applied force causes the colour regime to change from blue to red in the test piece's breaking area.

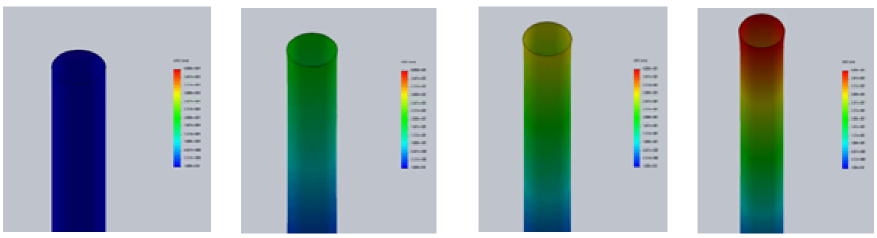


Fig.2: Visualization of stretching behaviour- variant A4

The elasticity module shows the lowest values for the C5 knit version, both in the horizontal direction (0.766 N/cm^2) and in the vertical direction (0.265 N/cm^2).

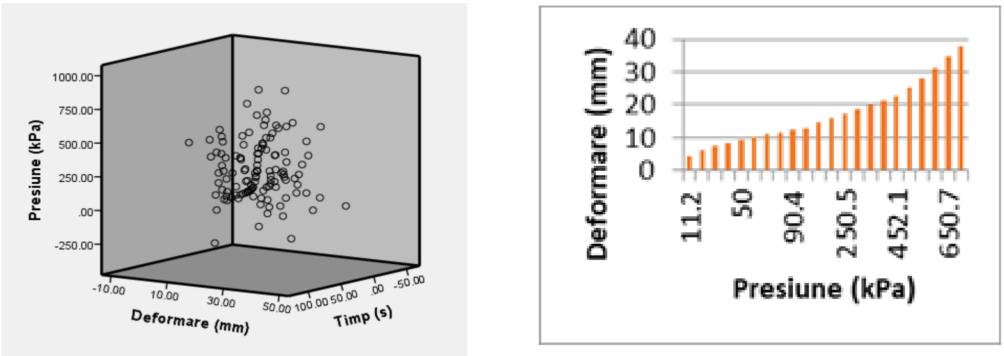


Fig. 3: Evolution of the deformation of textile materials depending on time and applied force-C5

The variant with the highest anisotropy is the C5 knit variant (2.89), which highlights different behaviour of elasticity in the two directions of the textile structure. The best anisotropy is presented by the woven fabric variant (0.42). A specialized professional program was used to highlight the evolution of the deformation of textile materials depending on time and applied force (Fig.3). The experiment set up of Lloyd materials testing equipment that is coupled together with a data acquisition unit-DAQ, the white box gives the relationship between the mechanical properties (strain/elongation/load), to electrical properties, the resistance of the conductive material. The measurements are determined simultaneously (Fig.4). The level of electrical resistance, force and strain variables at the beginning and the end of the strain 5% and 40% of the studied textile structures are presented in Table 3.

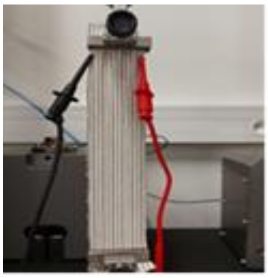


Fig. 4a) A4

Fig. 4b) C5

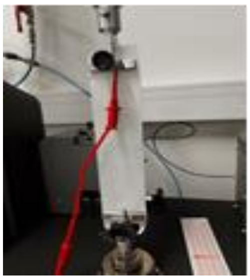


Fig. 4c) B4

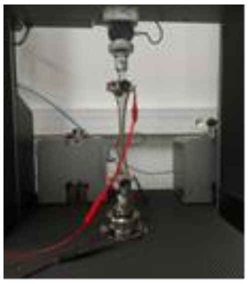


Fig. 4d) C6

Table: 3 Electrical resistance evolution

No	Samples	Time (s)	Resistance Ω	Load (N)	Strain	Observation
1	A4 (5%)	0,54	411,4	0,174	-0,004	Max.resistance:412,17 Ω/m at time:10,97 s, load:0,065N and strain: -2,4E-05
		51,56	410	-0,06	0,008	
	A4 (40%)	2,766	216,38	1,13	0,034	Max.resistance:425,7 Ω/m at time:193,75 s, load:76,39N and strain:0,4
		271,11	185,75	0,033	0,005	
2	C5 (5%)	1,66	417,06	1,04	0,004	Max.resistance:471 Ω/m at time:41,8 s, load:20,44N and strain:0,98
		142,26	276,79	-0,306	0,0097	

	C5 (40%)	2,68	410,42	0,541	0,007	Max.resistance:427 Ω/m at time:16,10 s, load:53,01N and strain:0,2122
		263,01	417,38	-0,401	0,048	
3.	B4 (5%)	0,844	427,7	0,71	0,0013	Max.resistance:429,65 Ω/m at time:50,68 s, load:0,387N and strain:1,08E-08
		82,78	425,52	0,403	7,57E	
	B4 (20%)	0,248	427,62	1,905	0,006	Max.resistance:433,36 Ω/m at time: 2,236s, load:0,516N and strain: -2,6-07
		12,67	427,05	242,26	0,173	
4	C6(5%)	0,53	7,55	0,37	1.53E	Max.resistance:12,18Ω/m at time:29,55s, load-0,259N and strain:0,0057
		52,66	12,38	0,2864	-1,08E	
	C6(40%)	2,73	21,20	1,231	0,022	Max.resistance:37,17 Ω/m at time:144,90s, load:0,791 and strain:0,311
		267,94	21,74	0,211	0,007	

The resistance of the fabrics that have in the structures metallic yarn and cotton yarn, changes between a minimum of 412,17 ohms/m (A4) to a maximum of 433,36ohms/m(B4) which **is within** the tolerable limits of the resistance of the conductive yarn of 76 ohm/m (yarn 1) – 220 (yarn 3) ohm/meter. The lowest value of the electrical resistance was obtained by the knit structure made only of conductive (yarn 1). In this case, the min./max value at the strain 5% was: 2,72 Ω/m/12,18 Ω/m and at the strain 40%:0,56 Ω/m/37,17 Ω/m. These values are in the limit of linear electrical resistance of the yarn (76 Ω/m).

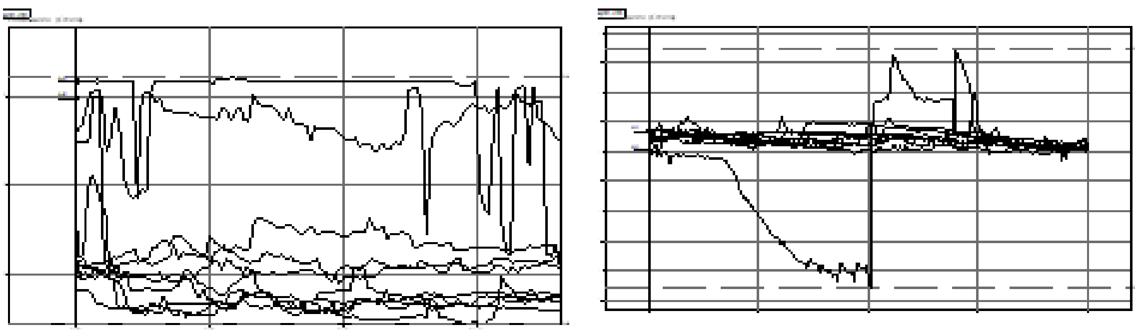


Fig. 5: The evolution of the electrical resistance (Ω/m) of sample C5 as a function of the applied strain of 5% and 40%

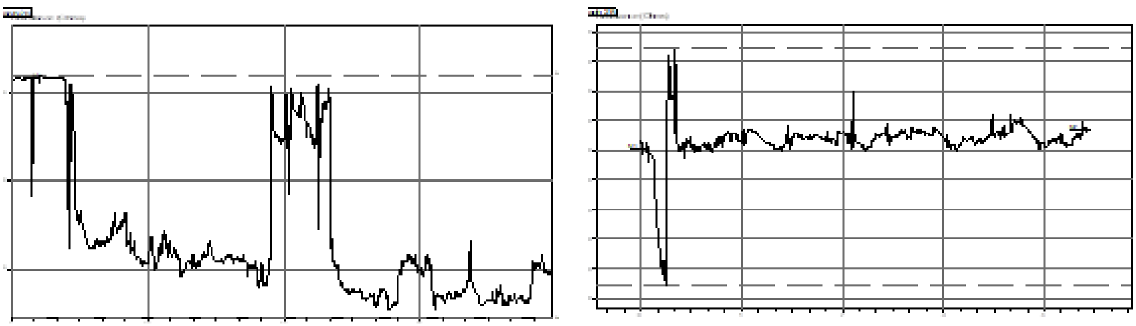


Fig.6: The evolution of the electrical resistance (Ω/m) of sample C5 as a function of the time at an applied strain of 5% and 40%

Fig. 5 shows the evolution of the electrical resistance (Ω/m) as a function of applied strain and fig.6 as a function of time for the C5 variant at an elongation at 5% and 40% and 5 cycles. There is some noise observed in the resistance measurements, due to the variation caused by the contact(s) resistance. The contact resistance is the resistance between two yarns in contact in the knit or the weave, these changes depend on the dynamics of the forces on the fabrics.

4. CONCLUSIONS

Conductive textile structures were made by using Statex yarns and Bekinox yarns (296-610 dtex) and applying classic knitting and weaving technologies. By using Lloyd materials testing equipment that is coupled together with a data acquisition unit-DAQ (white box) the evolution of linear electrical resistance (Ω/m) was obtained depending on the applied force and time. The electrical resistance of textile structures during deformation has higher limits compared to that of the constituent conductive threads. The lowest value of the electrical resistance was obtained by the knitted structure made only of metal conductive yarns. The electrical resistance is stable for up to 40% strain, especially for the woven fabric sample, compared to the knitted fabric sample. This aspect will be taken into account in the design of the new structures and in particular in the geometry of the insertion of the conductive wires and their structure also to avoid contact resistance between the yarns.

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