



Research Article

Role of Experimental Damage Mechanics for the Circular Economy Implementation in Cotton Industries

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Abstract

Objective: The objective of the current research was to study the effects of tensile properties of post-consumer cotton fabric on mechanical recycling and shredding. The effect of tensile properties like tensile force, effective tensile force, breaking force, elongation, yield strength on cutting and shredding of cotton textile was measured and demonstrated with literature investigations. In this work, we tried to develop the relationship between tensile testing, subjective assessment, and circular economy.

Methods: In this manuscript, the quality of post-consumer textile cotton was evaluated using American society for testing of materials (ASTM) D5034-95-08 grab test and the ASTM D5034-95-06 strip test. The fabric surfaces before and after mechanical testing were explored using a scanning electron microscope (SEM). Moreover, the subjective assessment was also performed to observe various physical properties at room temperature.

Results: The initial scanning electron microscope analysis has proved the damage and distortion in weft and warp directions. The tensile, effective tensile, and breaking force were 86 N, 143 N, and 75 N in the weft direction, and those were 180 N, 227 N, and 170 N in the warp direction. The deformation in terms of the extension was in the range of 10% to 27% in weft and 3% to 8% in warp direction. The scanning electron micrographs after testing confirmed the creation of microfibrils. These microfibrils connect with the fibre core through lignin.

Conclusion: Higher tensile, breaking force, and effective tensile force increase the purity and quality of the recycled product. The higher values play a vital role throughout operational steps of recycling for enhancement of performance and tactical properties. However, lower mechanical properties produced operation problems such as tangling, buckling, and mixing, which downgraded the quality and performance of polymer products. Technically, these investigations can add value to the concept of the circular economy.

Keywords: circular economy, mechanical testing, cotton polymer wastes, recycling, polymer processing

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1 INTRODUCTION

A circular economy (CE) is an industrial system that recycles and manufactures products with negligible wastes^[1]. CE originates from common industrial system theory^[2], cradle to cradle recycling^[3] and performance^[4]. CE has also emerged as an innovative solution for the transformation of end wastes, post-consumer wastes, and even end-of-life wastes into valuable recycled products^[5]. In the future, the world production of polymer and composite materials will surpass 105 million tons per year^[6,7]. The fast development and elevation in the production of polymer materials create huge textile waste, which boosts the development of recycling technology for textile manufacturing of products from its waste^[8,9]. The manufacturing technology of textile materials waste relies on the testing and characterization techniques^[10]. The textile manufacturing industries from yarn to fabric production produce pollution and relegate the sustainability of fibers^[11]. Cotton is a natural fabric textile material. The world cotton consumption surpassed 25 million tons per year^[12]. Due to environmental pollution^[13], energy consumption for cotton manufacturing^[14], carbon dioxide emission, the recycling of cotton gained importance after the fibers recycling revolution^[15].

Woven, knitted, non-woven, and braids are four basic structures of textile polymer materials. The minimum requirement of fabric tensile strength, engineering tensile strength (design force), elongation, breaking force, and young's modulus is important during cutting, shredding, and textile manufacturing^[16]. The tensile force is the maximum withstanding force required for the initiation and propagation of a tear under defined conditions. Tensile properties are the main attributes for the quality and performance of textiles fabrics in predicting suitability, durability, and service life during textile manufacturing, and quality testing. The fabric firmness, tightness, structure, size of yarns or fibers, and fabric design for manufacturing are especially predicted using tensile properties^[17]. The utilization of cotton textiles lowers its fiber quality. During recycling, this decrease in quality shortened the fiber length during mechanical cutting and shredding of cotton fabrics^[18].

The main techniques for testing tensile properties are tear, strip, and burst. The tensile testing was used to measure the engineering tensile strength (effective design strength), breaking force, stiffness, and elongation of textile fabric. Tensile properties of fabric rely on the strength of the yarn, linear density, directional thread densities, twist factor, fabric thickness, crimp level, and fabric skew. A Tear test was utilized to measure the minimum strength required for tear initiation. In the initial stage of tear testing, force concentrates on threads of fabric for tear initiation

and propagation. The breakage of threads shifts the load ultimately causes the failure of fabric^[19,21].

This research was designed to evaluate the mechanical properties of the post-consumer cotton polymer. The relationship between mechanical properties was developed and explained for circular economy implementation in polymer industries.

2 MATERIALS AND METHODS

2.1 Materials

The plain-woven post-consumer cotton polymer from the Estonian local industry has been used for characterization and tensile testing. The fabric samples had 237 grams per square meter weight (GSM) and 0.45 mm thickness. The yarn density was 36 threads/cm in warp and 18 threads/cm in the weft direction (Table 1).

The tensile strength, effective tensile strength, breaking strength, and elongation were determined using the mechanical testing machine. The tensile strip and grab tests were utilized. Both standard tests were carried out according to ASTM D5034-95 for grab test and ASTM D5035-95 for strip test.

2.2 Methods

All tensile tests were performed on an Instron tester model 5800. The size of lower and upper grip fixtures was maintained at 100 x 25.4 mm throughout the experimental study. The crosshead speed was 50 mm/min. Data collection, measurement, and analysis were conducted using data acquisition software. The load-displacement graphs were recorded to estimate effective tensile strength, Young modulus, tensile strength, breaking force, and elongation of textile cotton (Table 2).

2.3 ASTM D5034-08 (Grab Test):

American society for testing of materials (ASTM) D5034-95-05 grab test was used to measure effective tensile strength, breaking strength, and elongation, and is utilized for woven fabrics. Commonly tensile engineering force (design force) was measured for textile manufacturing.

2.4 ASTM D5034-06 (Strip Test):

This standard was used to estimate the breaking force and elongation of textile fabric. Ravelled strip and cut strip tests are two main types. Ravelled strip test was utilized for woven and cut strip test was used for knitted and non-woven fabrics. Formally, strip tests are considered useful for quality control and assurance attributes.

2.5 Equipment and Machines

The Instron universal testing machine was used to perform grab and strip tests. Mostly, these testing machines

Table 1. Physical Properties of Post-Consumer Cotton Textile

Physical Property	Units	Value	Physical Property	Unit	Value
Woven-Weft	-	Plain	Thread diameter in warp direction	mm	0.345
Woven-Warp	-	Plain	Thread diameter in warp direction	mm	0.345
Weight	grams-m ⁻²	237	Twist value	T/m	800
Warp linear density	cm ⁻¹	29	Thickness	mm	0.45
Weft linear density	cm ⁻¹	29	Weft-warp thread setting	cm ⁻¹	18x36

Table 2. Samples Dimensions of Post-Consumer Cotton Textile

Type	Specimen No.	Dimensions (mm)		
		Length	Width	Gauge Length
Grab (weft direction)	1-5	180	100	100
Grab (warp direction)	6-10	180	100	100
Strip (weft direction)	11-15	180	50	100
Strip (wrap direction)	16-20	180	50	100

used bluehill universal materials testing software for operations and data analysis. The software provides help to facilitates the control of the workflows. Moreover, Contour GT-K 3D optical microscope and mechanical profilometry (Mahr Perthometer) were introduced for cotton fabric surface evaluations. Finally, the scanning electron microscope (SEM) (Zeiss EVO® MA-15) was used for cotton fabric evaluation before and after testing.

3 RESULTS

3.1 SEM Characterization

Initially, the nature of pristine post-consumer cotton fabric was probed using SEM. Figures 1A-1F show SEM images of cotton fabric in the warp direction. The fibres are arranged in the vertical direction with twist values (800 T/m). The cotton polymer has round fibres along with drifting of cellulose lignin 1A (X 20). Additionally, the cotton waste also has similar surface like jogs, surface damage, and distortion. Under high magnification SEM images 1B (X 500), 1C (X 1.00 K) and 1D (X 5.00 K), the surface fibers damage and distortion were observed. The cotton polymer surface defects introduce functional problems during processing and recycling^[22]. Hearle et al.^[23] provided a detailed reference collection of more than 1500 SEM images. The collection revealed information about surface analysis, fiber ends, and cross-sections areas. Accordingly, they proved that newly manufactured textile woven products had a smooth surface. Additionally, fiber did not drift over yarns. Due to mechanical and chemical treatments during usability, the surface, fiber fineness, and

mechanical properties of the cotton fabric were damaged, distorted, and lowered, respectively. Thereafter, the nature of pristine post-consumer cotton fabric was probed using SEM in the weft direction. Figures 2A-2F show SEM images of cotton fabric in the weft direction.

The fibers are arranged in a parallel direction with twist values (800 T/m). The SEM images were shown the same behavior as of warp direction.

3.2 Comparative Analysis of Cotton Polymer for Tensile Force Properties

Tensile force and effective (design) tensile force resembled the maximum force with which cotton can withstand during textile manufacturing. The numerical values of tensile and effective tensile force are estimated in Tables 3-4 and shown in Figures 3A-3B, and Figures 4A-4B. In the strip test, the weft direction fabric tensile values (59.17-85.39N) are lower than warp direction tensile values (107.49-142.54N). Similarly, in the case of the grab test, the weft direction fabric effective tensile force values (143.41-179.19N) are lower than in warp direction effective tensile values (162.93-225.26N). This phenomenon is same to the numerical and graphical results of strip and grabs tests. Plain woven has the highest strength in warp direction due to high thread density (36 threads cm⁻¹), medium weight, and high number of crossover points in warp direction^[24]. Fundamentally, the tensile strength depends on the individual strength of yarns and fibers of threads^[25]. Therefore, an increase in above mentioned physical par-

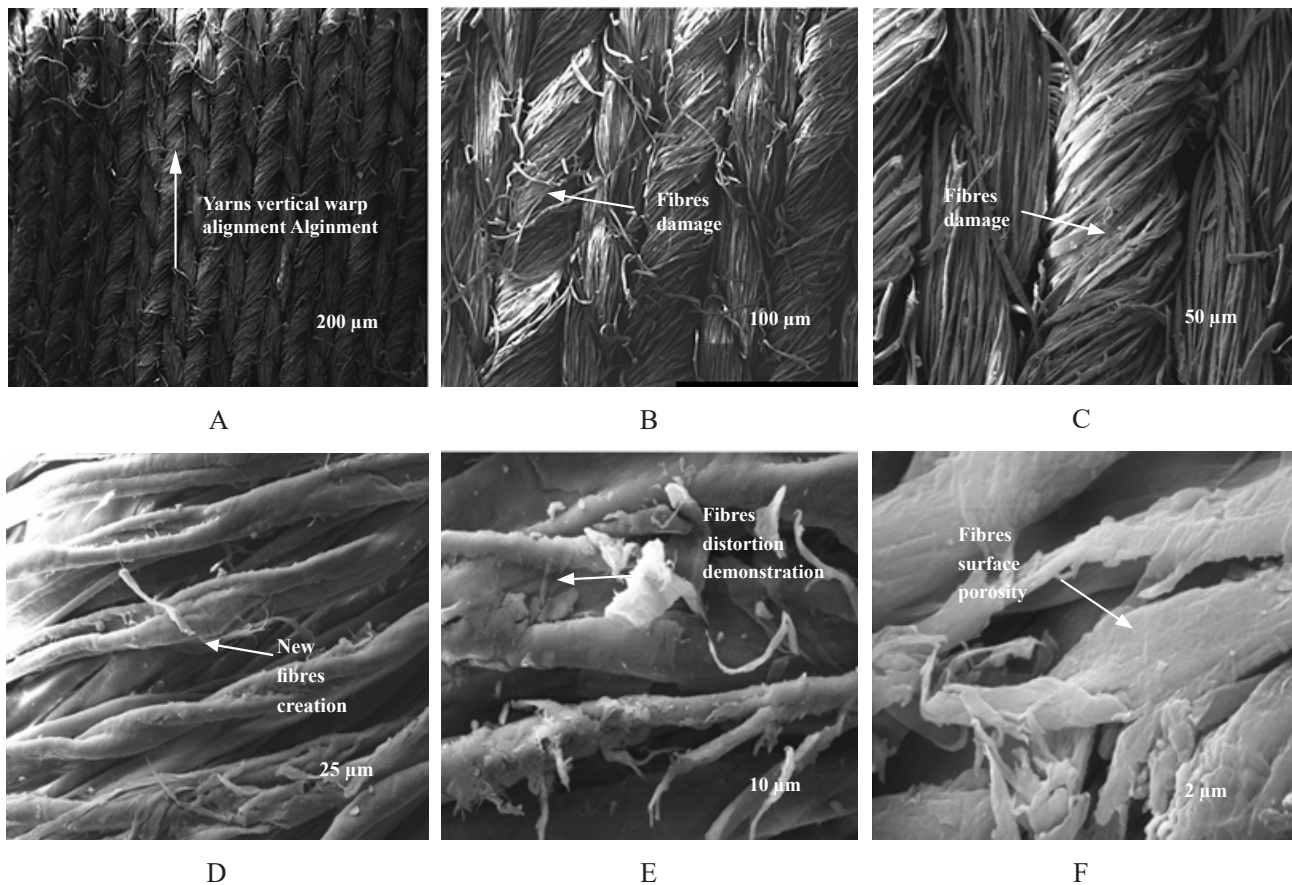


Figure 1. SEM images (A-F) of cotton fabric in warp direction at different magnifications. A: Weaving nature; B: Fibers drifting; C: Fibers damage; D: Cotton Fibers creation; E: Fibers distortion; F: Fibers porosity.

ameters increases the number of yarns, thread, and hence tensile strength of fabrics. Higher linear density, thread density, and weight decrease crimple level. The elongation under loading and stresses cause crimple interchange. Higher crimple levels decrease elongation^[26]. During loading low crimple along with other surface defects offer resistance for transfer of load. This phenomenon increases extension and decreases the tensile strength of fabric cotton. Besides this, a higher twist value causes an increase in tensile strength and a decrease in elongation.

3.3 Comparative Analysis of Cotton Polymer for Breaking Force Properties

At breaking force, the fracture of cotton-woven fabric occurred. The values of breaking force for strip test in weft and warp directions are mentioned in Table 3 and shown in Figures 3A-3B. In strip test value of fabric weft direction breaking force (43.54-73.29N) was lower than warp direction breaking force (95.29-123.65N). In the case of the grab test, the value of cotton weft direction effective breaking force (125.56-152.37N) was lower than warp direction effective breaking force (162.93-219.16N). The breaking force is directly related to the fabric's cross-sectional area of fabrics. S. ertugrul et al.^[27] proved that breaking force entirely relies on fabric weight, yarn individual breaking strength, and elongation at breaking point. In addition to warp and weft

directions, the increase in the above-mentioned parameters causes an increase in fracture force of the cotton textile. According to Figures 3C-3F and Figures 4C-4F, that are related to strip and grab tests, the higher the fracture force, the lower the elongation. It was assumed that twist value, crimp level, and plain structure of fabric contributed to these effects.

3.4 Comparative Analysis of Elongation During Testing

Elongation is a percentage increase in length with respect to its original length during testing. The elongation results for warp and weft directions are estimated numerically in Tables 3-4 and shown graphically in Figures 3A-3B and Figures 4A-4B. In the strip test, the cotton fabric weft direction percentage elongation (10-27%) was greater than warp direction percentage elongation (5-8%). In case of the grab test, the cotton weft direction percentage elongation (10-28%) was greater than warp direction percentage elongation (3-7%). Overall, the results proved that percentage increase in length was more in the weft direction than the warp direction. The thread density of the warp setting is more than the weft setting. The higher the thread setting density, the lower the crimp level^[28]. Therefore, the crimp level is higher in weft and lower in the warp direction; hence more crimp levels cause an increase in extension and a reduction in breaking and tensile force^[29-31]. The cotton fabric failure starts where elongation is at its minimum level^[32].

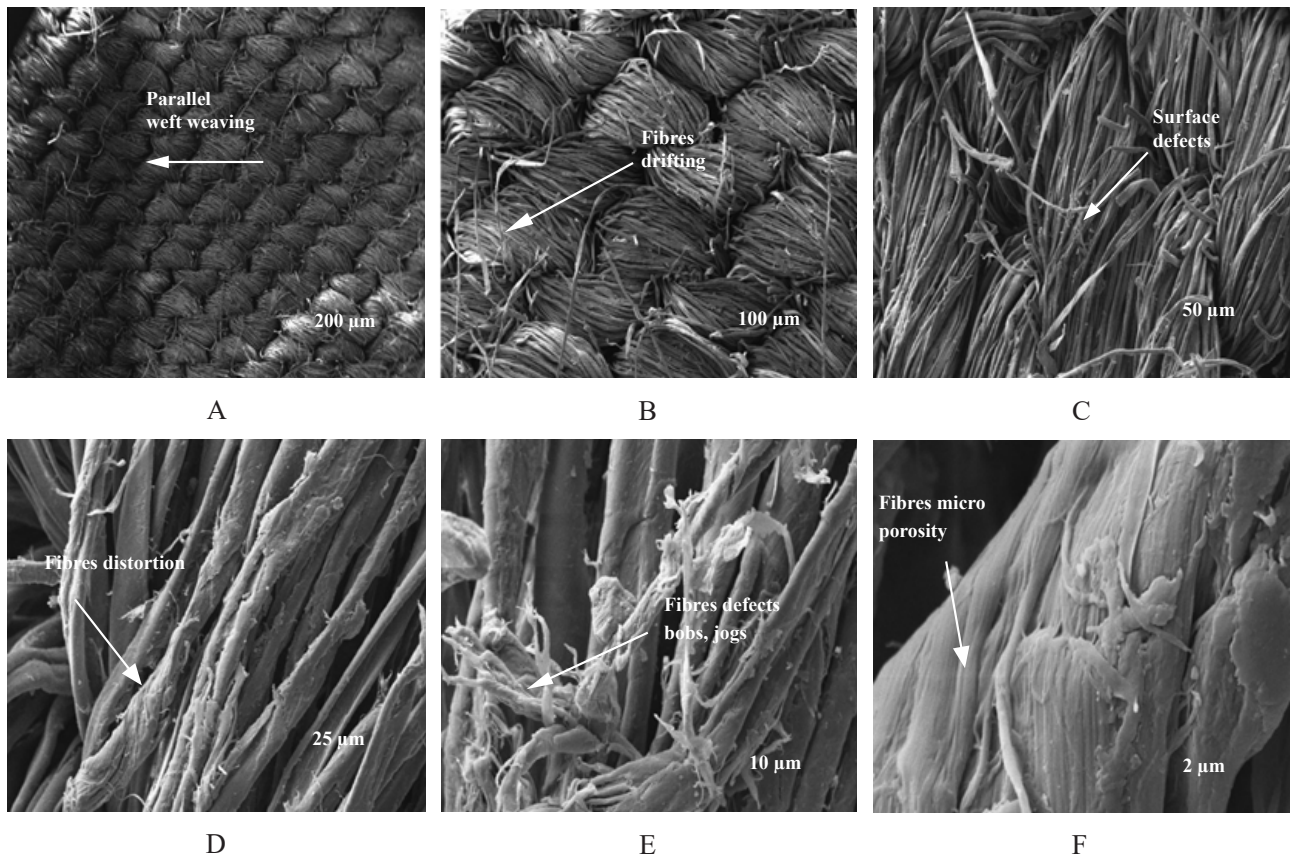


Figure 2. SEM images of Cotton Fabric in weft direction at different magnifications. A: Cotton weaving nature; B: Weft fibers drifting; C: Weft weaving defects; D: Weft fibers distortion; E: Fibers bobs and jogs; F: Fibers microporosity.

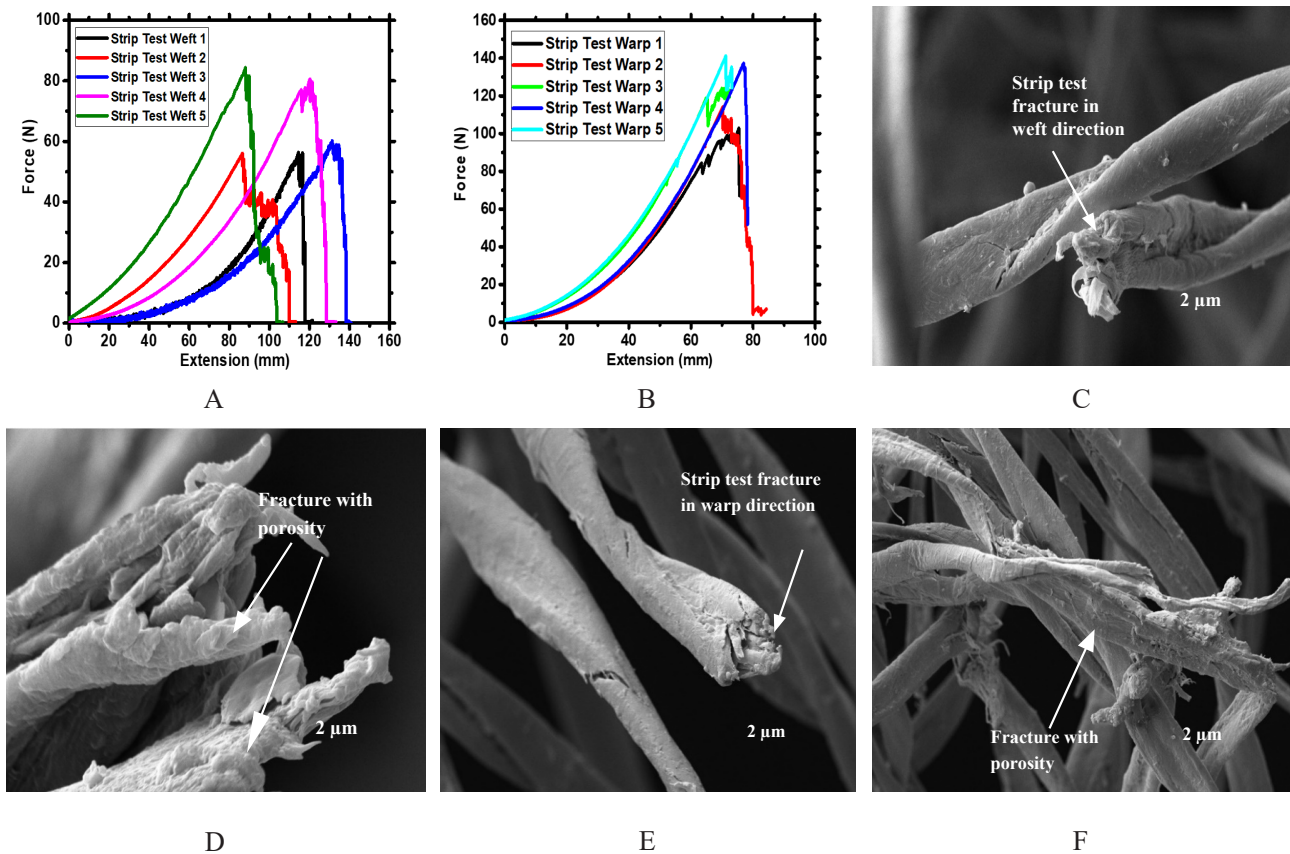


Figure 3. Cotton polymer strip tensile testing and SEM fracture characterization. A: Strip test in weft direction; B: Strip testing in warp direction; C: Typical SEM fracture micrograph in weft direction; D: SEM fracture micrograph with surface defects; E: Typical SEM fracture micrograph in warp direction; F: SEM fracture micrograph with surface defects.

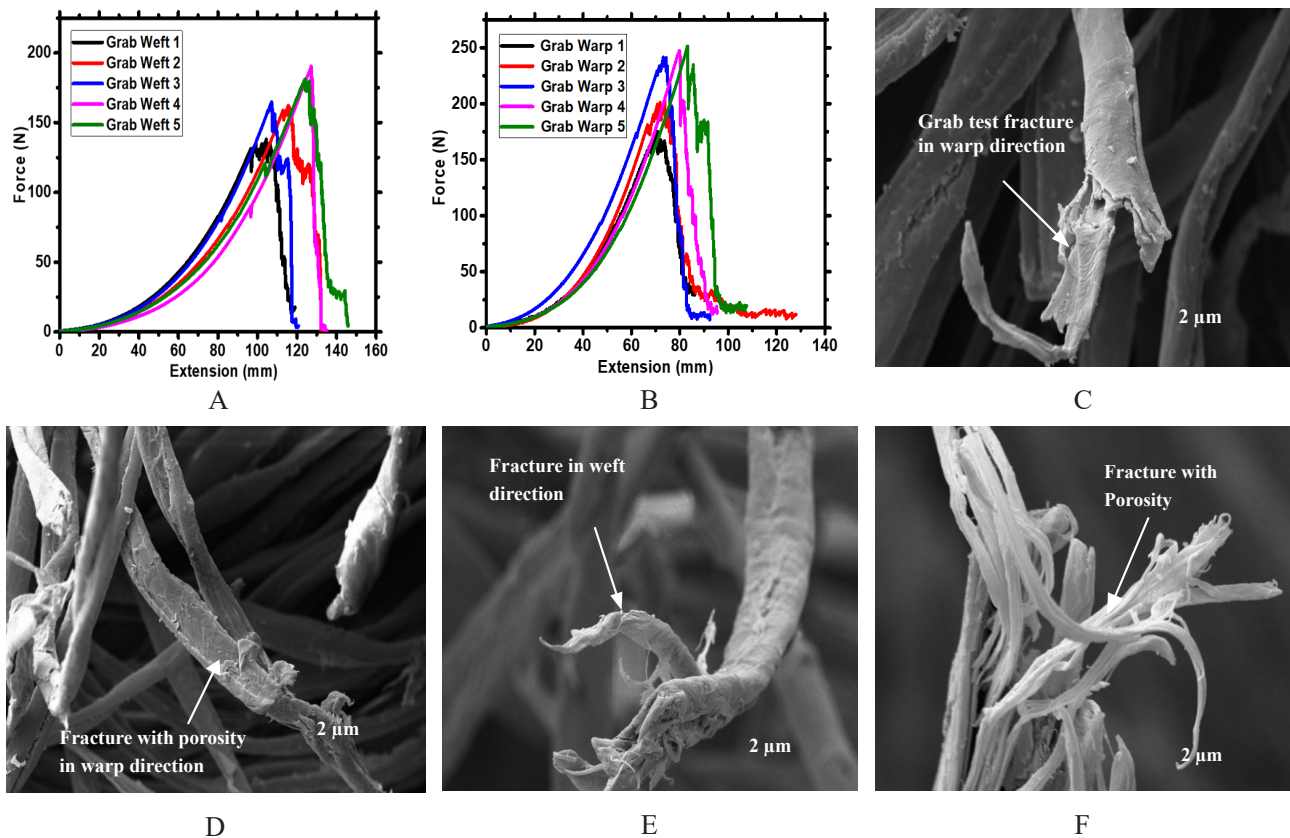


Figure 4. Cotton polymer grab testing and SEM fracture characterization. A: Grab test in weft direction; B: Grab test in warp direction; C: Typical SEM micrograph of fracture in warp direction; D: Warp SEM micrograph of fracture with defects; E: Typical SEM micrograph of fracture in weft direction; F: Weft SEM micrograph of fracture with defects.

3.5 Fabric Failure and Micromorphology

Figures 3C-3F and Figures 4C-4F show the woven fracture of the fabric. The hundreds of fibres merge to constitute a yarn. These yarns blend at a specific twist angle for fabric manufacturing. The mechanical failure of cotton fabric was characterized using scanning electron microscopy (SEM). The cotton fibres deformed and failed with flat and bulbous shapes. The flat fibres being straight and bulbous being unsymmetrical. After performing the tests on the machine on a large number of cotton fabrics, we concluded that deformed materials accumulate basilar side of fibres. At first, the applied load shared by fabric yarns, which transferred the applied load to adjacent fabric yarns. During testing, the cotton fabric fractured due to failure of a single thread at a time, or due to a very small group of woven threads. The produced distortion creates skewing and slippage phenomena in threads over each other. Therefore, the fracture of the cotton polymer ultimately occurs.

4 DISCUSSION

Mechanical evaluations, especially tensile testing, play a vital role in the prediction of polymer wastes performance during processing for circular economy implementation^[33-35]. The complete processing of polymers especially wastes consist of collection, sorting, separation, cutting, grinding, mixing, manufacturing and finishing operational steps. The

transformation of newly manufactured polymer products into waste lowered the mechanical, surface and tribological properties. The decrease in mechanical properties especially due to service life create functional issues such as tangling, buckling, machinery parts erosion and metallic surface fatigue. During an interaction in various operation steps, the higher tensile properties impart suitable contact between polymer and metallic surfaces of machinery parts. Kothari et al. proved that mechanical and tactical properties of cotton textile primarily rely on strength of individual yarns, fabric linear density, fabric thread density in warp and weft directions and fabric weight. Fabric properties also depend on fabric structure, twist value, crimp level and fabric thickness. According to experimental results, the increase in primary properties gives rise to elevation in mechanical properties of cotton fabric. As per Tables 3-4 and Figures 3A-3B and Figures 4A-4B, the evaluated tensile properties for instance tensile force and fracture force and effective tensile force values are greater for warp direction and lower for weft direction, which provide a strong foundation^[36] for fabric fineness, comfort, softness^[37], durability, stretching and finishing of surface^[38]. Nevertheless, continuous cyclic mechanical and chemical treatments^[39], for instance, calendaring, embossing^[40], brushing, dry cleaning^[41], bleaching and laundering^[42,43] lowered the mechanical properties of fabric textiles. These mechanical and chemical

Table 3. Tensile Strip Test Results of Post-Consumer Cotton Textile

Specimen No.	Weft Direction			Wrap Direction		
	Tensile Force (N)	Breaking Force (N)	Extension (%)	Tensile Force (N)	Breaking Force (N)	Extension (%)
1	59.17	43.54	17	107.49	95.29	6
2	55.19	39.76	12	114.63	99.86	7
3	59.86	54.93	28	125.19	109.42	4
4	83.27	69.25	27	139.57	120.93	8
5	85.39	73.29	10	142.54	123.65	5

Table 4. Tensile Grab Test Results of Post-Consumer Cotton Textile

Specimen No.	Weft Direction			Wrap Direction		
	Effective Tensile Force (N)	Breaking Force (N)	Extension (%)	Effective Tensile Force (N)	Breaking Force (N)	Extension (%)
1	143.41	125.56	10	180.83	162.93	5
2	164.98	145.5	20	206.51	175.42	7
3	172.65	147.14	10	248.55	225.26	3
4	187.51	170.71	28	251.37	218.79	3
5	179.19	152.37	25	257.42	219.16	5

treatments decrease the fineness, comfort and durability of fabric cotton. Hence, performance, and quality of post-consumer textiles become poor. Furthermore, a significant difference in calculated and literature values^[44,45] also demonstrated the same phenomenon. Based on calculated and literature results, it was assumed that a decrease in tensile properties creates a decrease in the performance of tactical properties of manufactured fabrics. Therefore, recycling and the circular economy of textile fabrics directly rely on the tensile and tactical properties of a textile. Based upon tensile testing results^[46] and subjective assessment^[47,48], the textile waste can be classified into end waste, post-consumer waste and end of life waste. The classification of textile wastes contribute to decide the recycling technique for processing.

5 CONCLUSION

In this novel work, the physical and tensile properties of post-consumer textile cotton have been explored for circular economy and recycling technology. Initially, weft direction tensile force (59.17- 85.39N), warp direction tensile force (107.49-142.54N), weft direction design force (143.41-179.19N), warp direction design force (180.83-257.42N), weft direction breaking force (43.54-152.37N), warp direction breaking force (95.29-219.16N), weft direction percentage elongation (28%) and warp direction percentage elongation (8%) have been determined. Moreover, the physical properties of as-received post-consumer textile was also calculated.

Based upon explored results, it has culminated that

woven fabrics hold superior properties (all tensile, physical, and tactical) in the warp direction. Due to lower values of tensile, design force, breaking forces, fineness, and comfort in the weft direction, the polymer cotton wastes create problems during recycling.

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Conflicts of Interest

The authors have no conflict of interest.

Author Contribution

Abrar H has studied and wrote this article. Abbas MM has reviewed and corrected this article.

Abbreviation List

ASTM, American society for testing of materials
 CE, Circular economy
 cm, Centimeter the unit of length
 GSM, Grams per square meter weight
 GT-K 3D, Model of optical profilometer machine
 m, Meter the unit of length
 min, The unit of time
 mm, Millimeter the unit of length
 N, Newton the unit of force
 SEM, Scanning electron microscope
 T/m, Number of twists per meter for fabric yarns

X, Symbol for magnification of Scanning electron microscope
Zeiss EVO® MA-15, Model of Scanning electron microscope machine
%, Symbol for percentage extension for cotton fabrics

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