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FIBRES & TEXTILES in Eastern Europe
Research Article • DOI: 10.2478/ftee-2023-0027 FTEE • 31(3) • 2023 • 46–55

Investigation into the Strength Properties of Plain Cotton Fabrics after Water Immersion for Upcycling Textiles

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Abstract

This study utilized SEM to examine the fiber structure of cotton stock fabrics and tested their durability based on ISO standards. Two types of cotton stock fabrics were evaluated: natural-colored (162 cm width, 120.8 g/m² weight, 281/10 in × 252/10 in density) and black-colored (157 cm width, 136.1 g/m² weight, 482/10 in × 210/10 in density). Prolonged water immersion caused surface yarns to loosen, fibers to expand, and the cross-sectional area to increase. Residual pulp and impurities on the fabric adhered to fibers. After 27 days, fiber looseness peaked, leading to complete breakdown after 30 days. Natural-colored fabric experienced significant weft strength loss within 12 days, while black fabric showed slightly higher weft strength loss after 36 days. Color changes were prominent in natural-colored fabric during the initial 21 days, while black fabric displayed noticeable changes after 12 days of immersion.

Keywords

Upcycling, cotton stock fabric, water immersion, strength properties.

1. Introduction

The production and consumption of clothing have led to a significant accumulation of unused fabric, resulting in waste issues [1]. However, the upcycling of stock fabric is currently ineffective [2], and there is limited research on this topic [3]. Moreover, the reliance of the textile industry on natural resources, particularly cotton, raises concerns about resource depletion and environmental pollution.

This study aims to investigate the properties of recycled cotton stock fabric to improve upcycling efficiency and minimize wastage. The evaluation includes breaking strength, tensile strength, and colorfastness to various conditions after different storage times [4]. The data obtained will establish physical performance index limit values and storage times for such fabrics, laying the groundwork for upcycling standards.

The significance of upcycling waste textiles, especially in countries like China, Vietnam, and South Korea with substantial amounts of unused stock fabric, is emphasized [5]. By diverting stock fabric from landfills and incineration, the textile industry can reduce environmental pollution, preserve land resources, and promote sustainability [6].

Figure 1 highlights the global distribution of waste, underscoring the urgency to reduce waste generation [6]. Additionally, the economic benefits of upcycling stock fabric are emphasized, considering the heavy reliance on imported textiles and raw materials by textile-producing countries [7].

Disposal methods such as landfilling and incineration have adverse environmental impacts [8]. Synthetic fibers, predominant in stock fabric, do not biodegrade completely, and incineration emits harmful gases, contributing to pollution [9]. Reusing stock fabric can substantially reduce carbon dioxide emissions, water consumption, and chemical usage, thereby mitigating the ecological footprint of the textile industry [10].

By developing a systematic testing system for stock fabric, this study aims to enhance production efficiency and minimize wastage resulting from ineffective fabric assessments. The system proposed will facilitate the classification and sorting of stock fabric, enabling informed decisions on its usability while reducing testing time, labor, and costs [11].

In conclusion, this research aims to contribute to the establishment of a sustainable and efficient upcycling process for stock fabric. Accurate assessment of its strength properties, along with reduced wastage and enhanced reusability, can unlock the potential of upcycling textiles and promote a circular economy in the textile industry.

Fabrics made of non-synthetic fibers constitute a substantial portion of the world's stock fabric supplies, and they are susceptible to environmental factors that can affect their properties. Among non-synthetic fibers, cotton is the most abundant, and hence, this research is centered on the performance of stock fabric that contains cotton fibers. By studying the physical properties of cotton, it is possible to use the extreme colors of natural and black cotton stock fabric to estimate the quality of all cotton stock fabric using quality-prediction equations and correlation coefficients.

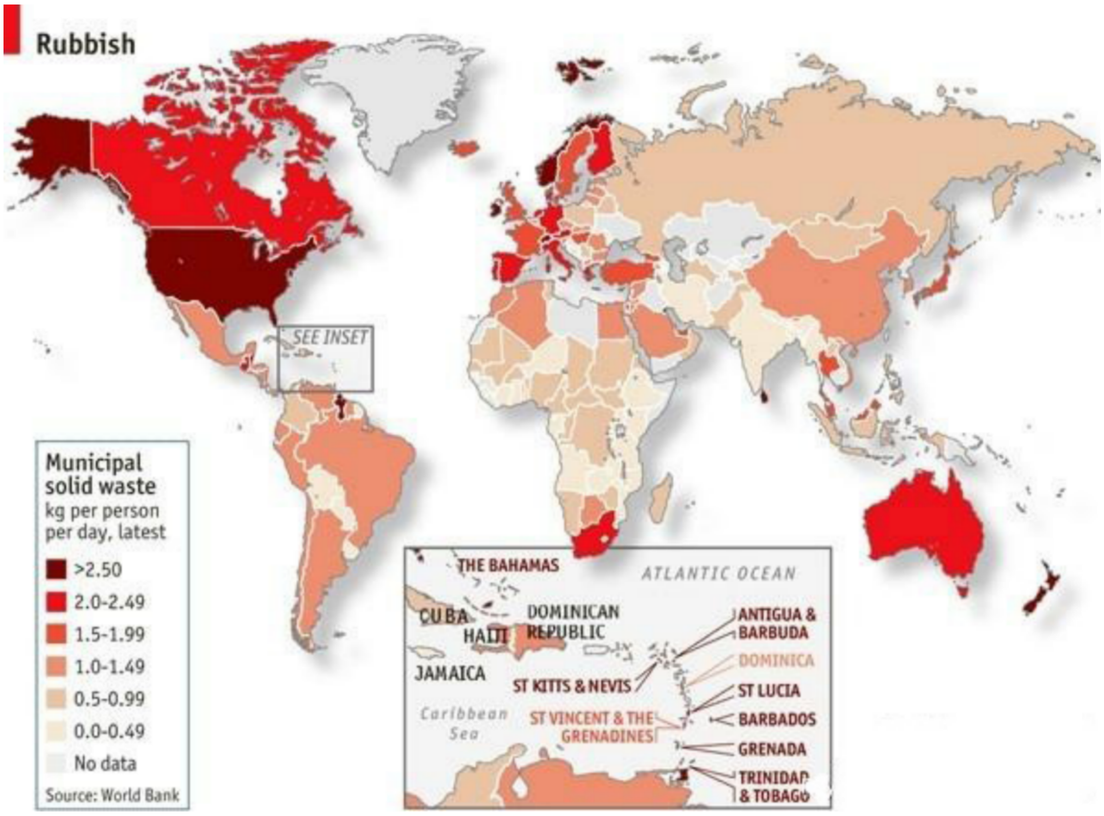


Fig. 1. Global rubbish distribution map [6]

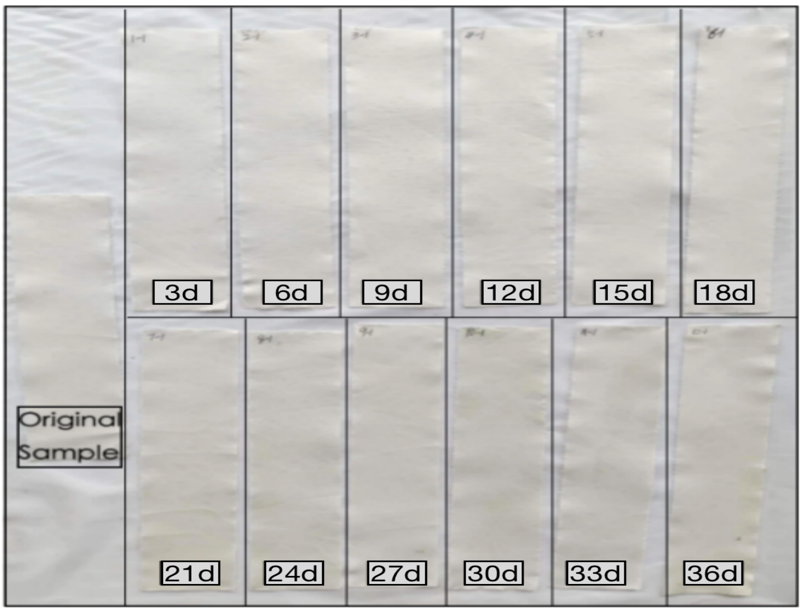


Fig. 2. Natural-colored stock fabric samples after water immersion, showcasing the original sample and 12 subsequent samples at different time intervals

The strength and color of stock fabric are the most important factors in determining whether it can be reused, as stock fabric is susceptible to environmental exposure, such as sun and rain. Therefore, our research includes exposure to natural light and heat, UV radiation, and water immersion, along with a supplementary test to determine colorfastness.

2. Experimental Samples

In this study, we used cotton stock fabric with specifications as described in Table 1. The experimental samples included black and white fabrics from the stock, and data from other colors were within the range of these two extremes. For research purposes, we selected plain and poplin fabrics due to their simplicity and stable performance. These fabrics are among the most commonly produced cotton fabrics and possess properties that are widely applicable [12].

Figure 2 displays natural-colored stock fabric samples immersed in water, comprising 12 pieces soaked for varying durations in addition to one original sample. The changes in color of the fabrics observed become increasingly apparent with extended soaking time.

Figure 3 illustrates black-colored stock fabric samples immersed in water, consisting of 12 pieces soaked for varying durations in addition to one original sample. The results demonstrate evident

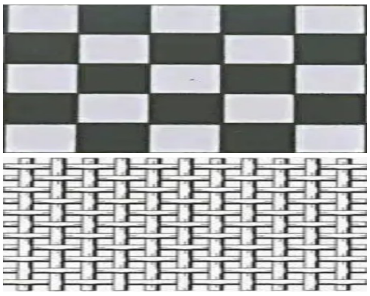
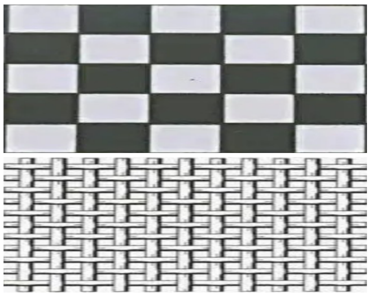
Parameter	Natural-color Stock Fabric	Black Stock Fabric
Composition (%)	Cotton 100	Cotton 100
Weave	 Woven	 Woven
Width (cm)	162cm	157cm
Weight (g/m^2)	120.8	136.1
Category	Plain	Poplin
Warp (/10 in)	281	482
Weft (/10 in)	252	210
Sample		
Sample size (mm)	250 × 50	250 × 50
SEM (100×)		

Table 1. Cotton stock fabric test sample specifications

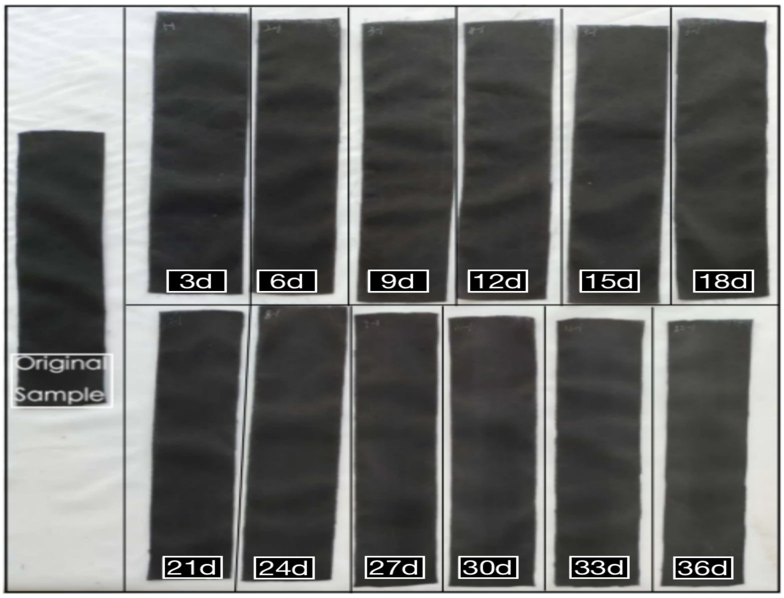


Fig. 3. Black-colored stock fabric samples after water immersion, showcasing the original sample and 12 subsequent samples at different time intervals

changes in both the color and luster of the fabrics with prolonged soaking time.

3. Fiber Strength Test

The strength of stock fabric can be evaluated using different measures, including tearing, bursting, joint, joint slip, peel joint slip, and peel strength. Among these, tensile breaking strength is considered a crucial indicator of the physical properties of stock fabric [13]. However, long-term storage of stock fabric exposes it to various factors, including temperature, humidity, and inventory time, which can lead to a decrease in its physical properties and service life. This section analyzes the change in tensile strength of stock fabric stored after water immersion, which is of great significance to the preservation of stock fabric.

In this section of the study, natural and black plain cotton stock fabrics were used as experimental materials. As previously mentioned, natural and black represent the two extremes of fabric dye chroma. By investigating the strength loss rate of cotton stock fabrics in these two extreme colors after water immersion, the change trends of the strength loss rate for other colored cotton stock fabrics with varying chroma values can be estimated (Note: the material itself, as well as auxiliary materials, can also affect the change trend of the strength loss rate). Therefore, this study utilized trend prediction equations and correlation coefficients derived from experiments conducted with natural-colored and black-colored cotton stock fabric to predict the change trend of the strength loss rate for all cotton stock fabrics stored after water immersion. The change trends for other colored stock fabrics are expected to vary between the two extreme colors, with lighter colors trending closer to natural cotton stock fabric and darker colors to black cotton stock fabric.

The fabric samples were placed under environmental conditions of 20 ± 2 °C and 65 ± 2% humidity for a duration of 24 hours. Subsequently, the test fabrics were precisely cut into pieces measuring 250 mm in the warp direction and 50 mm in the weft direction. Each end of the test fabric was securely clamped using a tester, employing a clamping length of 200 mm and a constant tensile speed of 20 mm/min. This study utilized a YG026H electronic fabric strength testing machine from Qingdao Hongda Textile Machinery Co., Ltd., with an error margin of ≤0.02%F·S. A total of 30 groups of stock fabric samples were tested for each piece, and any abnormal data points were eliminated prior to calculating the average test data.

$$\text{Strength Loss Rate} = \frac{\text{Breaking Strength(Original)} - \text{Breaking Strength(Current)}}{\text{Breaking Strength(Original)}} \times 100\%$$

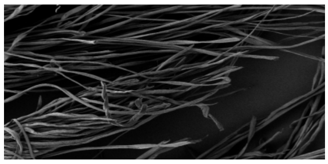
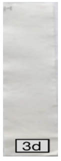
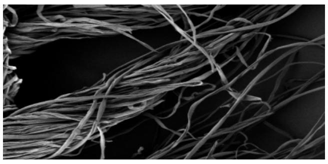
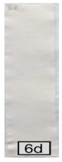
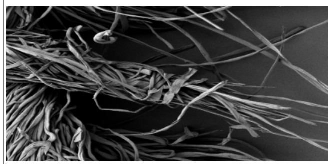
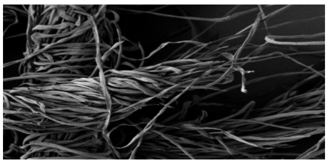
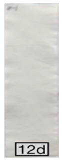
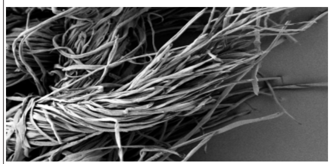
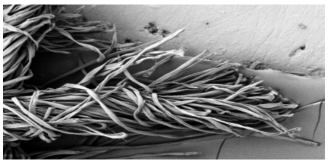
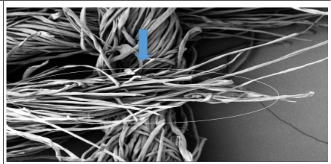
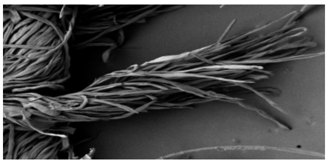
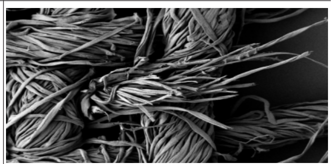
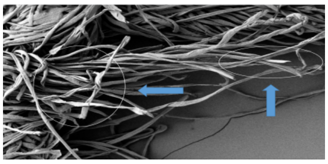
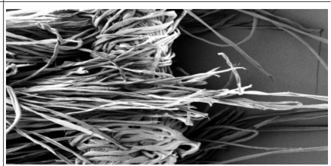
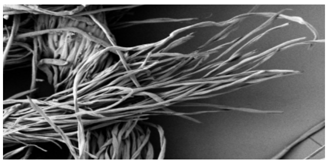
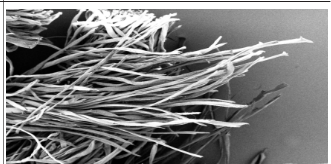
Time (day)		SEM (100×)	
 Original Sample			
Time	SEM (100×)	Time	SEM (100×)
 3d		 6d	
 9d		 12d	
 15d		 18d	
 21d		 24d	
 27d		 30d	
 33d		 36d	

Table 2. Fracture appearance of cotton stock fabric after water immersion

As stated earlier, the strength loss rate can be calculated using the formula provided above, where it is determined by dividing the difference between the strength values before and after water immersion by the strength value before soaking the fabric in water.

Table 2 presents the appearance of the fracture surface of cotton stock fabric after water immersion. It can be observed that before immersion, the original control sample is torn, displaying a clean fiber fracture opening without any longitudinal cracks following the fiber. As the immersion time progresses, the breaking positions of each fiber in the yarn fracture opening of the cotton stock fabric start to diverge. The outer fibers of the yarn experience increasing damage with prolonged immersion, resulting in strength loss that causes the outer fibers to break upon exposure to external forces. The fiber strength toward the center of the yarn is somewhat better, leading to relatively uniform breaking point positions. After 18 days of immersion, the yarn volume starts to expand, but its strength is compromised. Consequently, when it breaks, it appears relatively elongated. Following 27 days, the yarn fractures and distinct longitudinal cracks across the fibers become evident.

The relationship between the soaking duration and warp-breaking strength of natural-colored cotton stock fabric after water immersion is shown in Figure 4. The figure demonstrates that as the soaking duration increases, the warp-breaking strength of the fabric decreases. Particularly, the reduction rate of strength seems to speed up after 24 days.

Table 3 shows the matching equation derived from Figure 4. Since the data have no large fluctuations, and the curve is very good, we used the univariate cubic curve equation. The fitting degree of this prediction equation was also high, with a COD value of 0.99213.

The correlation between the immersion time and warp strength loss rate for natural-colored cotton stock fabric after water immersion is illustrated in Figure 5. The results indicate that as the immersion time increases, the rate of warp strength loss also increases, and there is a noticeable acceleration in the loss rate after 24 days.

Table 4 shows the matching equation derived from Figure 5. Because of the sudden acceleration in the warp strength loss rate after 24 days of immersion, the fitting degree of this power function is reduced to 0.97772.

The relationship between the weft-breaking strength and immersion time for natural-colored cotton stock fabric after water immersion is depicted in Figure 6. The results demonstrate that the weft strength decreases rapidly during the first 12 days and then gradually slows down before eventually stabilizing.

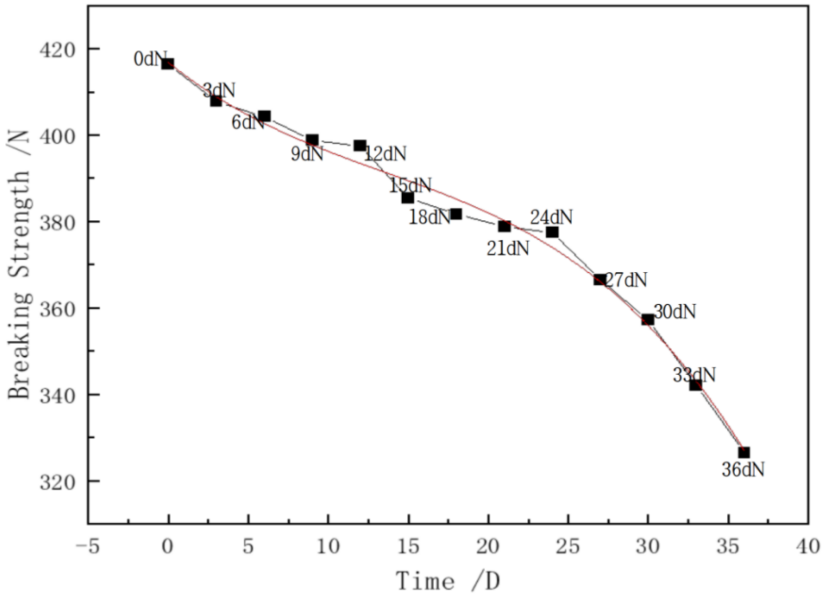


Fig. 4. Warp-breaking strength curve of natural-color stock fabric as a function of the water immersion time, along with the fitted polynomial

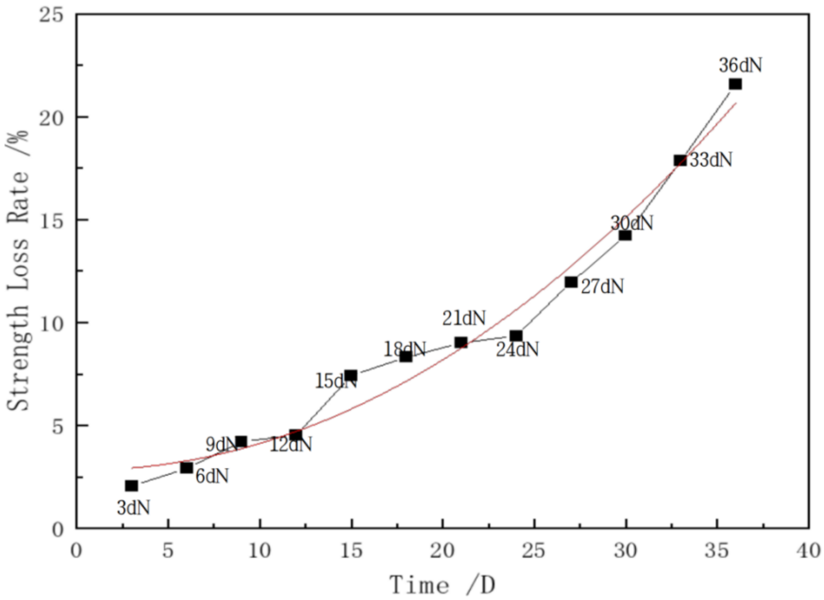


Fig. 5. Warp strength loss rate curve of natural-color stock fabric as a function of the water immersion time, along with the fitted polynomial

Table 3. Variation equation of the warp-breaking strength of natural-color stock fabric with the water immersion time.

Item	Value
Equation	y = Intercept + B1*x^1 + B2*x^2 + B3*x^3
Intercept	416.81931 ± 2.30958
B1	-2.98305 ± 0.57912
B2	0.12271 ± 0.03832
B3	-0.00303 ± 6.9863E^{-4}
R Squared (COD)	0.99213

Item	Value
Equation	y = a + b*x^c
a	2.82614 ± 0.69975
b	0.01178 ± 0.01136
c	2.0436 ± 0.26749
R Squared (COD)	0.97772

Table 4. Variation equation of the warp strength loss rate of natural-color stock fabric with the water immersion time

Item	Value
Equation	y = Intercept + B1*x^1 + B2*x^2 + B3*x^3
Intercept	361.06445 ± 5.59434
B1	-13.77009 ± 1.40277
B2	0.41888 ± 0.09282
B3	-0.00453 ± 0.00169
R Squared (COD)	0.98841

Table 5. Variation equation of the weft-breaking strength of natural-color stock fabric with the water immersion time

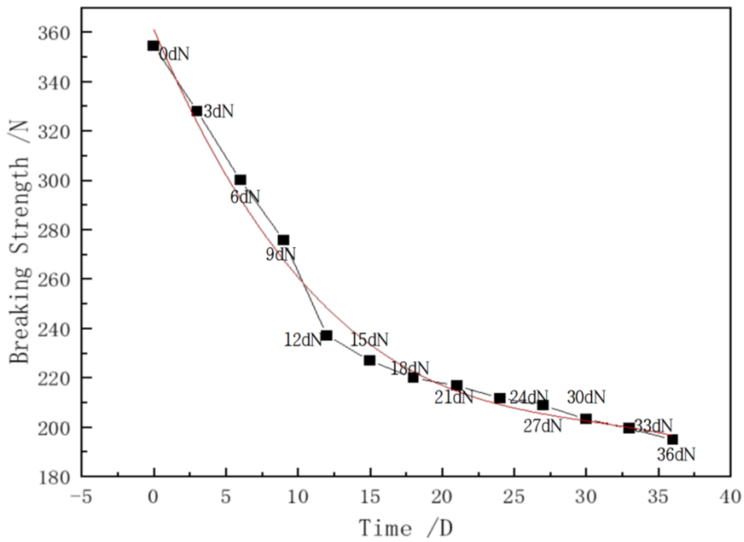


Fig. 6. Weft-breaking strength curve of natural-color stock fabric as a function of the water immersion time, along with the fitted polynomial

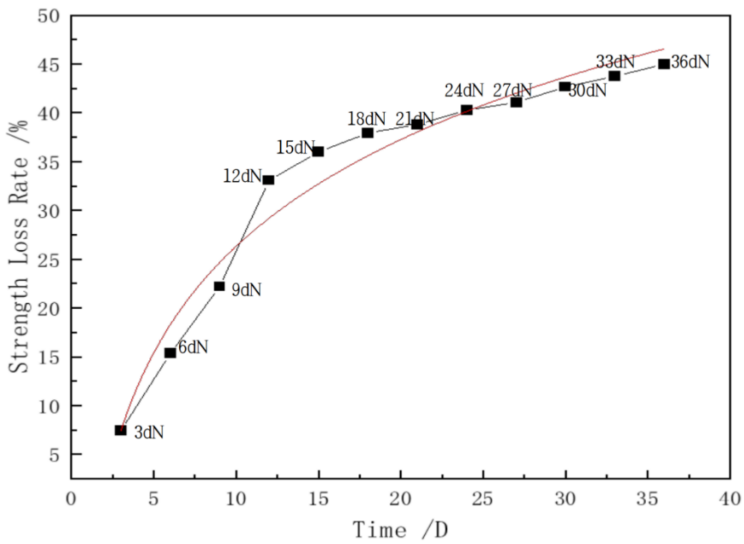


Fig. 7. Weft strength loss rate curve of natural-color stock fabric as a function of the water immersion time, along with the fitted polynomial

Table 5 shows the matching equation derived from Figure 6. Because there were no significant fluctuations in the data and a curved trend was observed, we adopted the univariate cubic curve equation, which gave a COD value of 0.98841.

The relationship between theweft strength loss rate and immersion time for the natural-colored cotton stock fabric after water immersion is presented in Figure 7. The results indicate that the strength loss rate increases rapidly during the first 12 days of immersion. However, after this period, the rate slows down and maintains a stable trend.

Table 6 shows the matching equation derived from Figure 7. Because of the sudden change in the weft strength loss rate of natural-colored cotton stock fabrics after approximately 12 days of immersion time, some of the data at this point deviates from the predicted curve. Therefore, the fitting degree of this equation is relatively low, with a COD value of 0.9671.

The relationship between the warp-breaking strength and immersion time for the black-colored cotton stock fabric after water immersion is depicted in Figure 8. The strength of the fabric shows stability during the initial 15 days of immersion. However, after this period, the rate of strength reduction begins to accelerate more rapidly, without any noticeable fluctuations.

Table 7 shows the matching equation derived from Figure 8. Because the test data do not show large fluctuations nor a clear curve trend, we adopted the univariate cubic equation and obtained a COD value of 0.99342.

The relationship between the warp strength loss rate and immersion time for black-colored cotton stock fabric is demonstrated in Figure 9. The figure shows that although the strength loss rate fluctuates within the range tested, it remains consistent with the overall trend, indicating a relatively stable relationship

Item	Value
Equation	y = a + b*x^c
a	-4761.23452 ± 240347.01947
b	4751.43356 ± 240340.24304
c	0.00329 ± 0.16514
R Squared (COD)	0.9671

Table 6. Variation equation of theweft strength loss rate of natural-color stock fabric with the water immersion time

Item	Value
Equation	y = Intercept + B1*x^1 + B2*x^2 + B3*x^3
Intercept	554.12959 ± 3.86116
B1	0.34807 ± 0.96818
B2	-0.15123 ± 0.06406
B3	$9.20422E^{-4}$ ± 0.00117
R Squared (COD)	0.99342

Table 7. Variation equation of the warp-breaking strength of black stock fabric with the water immersion time

Item	Value
Equation	y = a + b*x^c
a	1.13831 ± 0.77734
b	0.02858 ± 0.02007
c	1.88035 ± 0.19398
R Squared (COD)	0.9867

Table 8. Variation equation of the warp strength loss rate of black stock fabric with the water immersion time

Item	Value
Equation	y = Intercept + B1*x^1 + B2*x^2 + B3*x^3
Intercept	237.00269 ± 1.84906
B1	-1.08479 ± 0.46365
B2	-0.12965 ± 0.03068
B3	0.00224 ± $5.59328E^{-4}$
R Squared (COD)	0.99728

Table 9. Variation equation of the weft-breaking strength of black stock fabric with the water immersion time

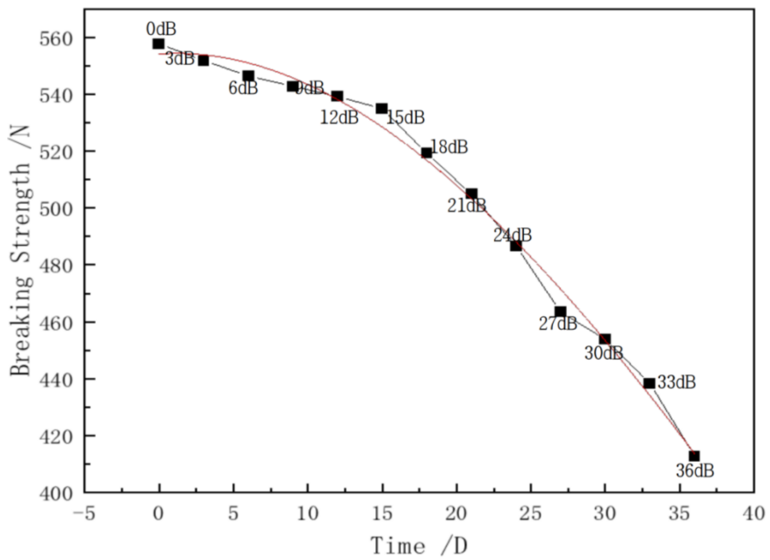


Fig 8. Warp-breaking strength curve of black stock fabric as a function of the water immersion time, along with the fitted polynomial.

between the warp strength loss rate and immersion time for black cotton stock fabric.

Table 8 shows the matching equation derived from Figure 9. Since there are no significant fluctuations in the test data and an overall curve trend was evident, we adopted the power function equation. The COD value of the fitting degree was 0.9867.

The relationship between the weft-breaking strength and immersion time for black-colored cotton stock fabric after water immersion is demonstrated in Figure 10. The figure shows that the weft strength of black cotton stock fabric remains relatively stable despite a gradual decrease in strength with increasing immersion time.

Table 9 shows the matching equation derived from Figure 10. Since the trend of the test data is very stable, the fitting degree of the equation is very high, with a COD value of 0.99728.

The relationship between the weft strength loss rate and immersion time for black-colored cotton stock fabric after water immersion is depicted in Figure 11. It can be observed from the graph that the weft strength loss rate tends to increase with prolonged immersion time, but eventually reaches a stable state.

Table 10 shows the matching equation derived from Figure 11. Again, since the changing trend of the test data is very stable, the fitting degree of the equation is very high, with a COD value of 0.9921.

4. Results and analysis

The possibility of repurposing the existing fabric in terms of its performance is highly reliant on its strength and color. Therefore, it is essential to examine the patterns of strength and color changes in the existing fabric and create equations to calculate the viability of repurposing it. Making prompt decisions is crucial in determining the feasibility of repurposing the fabric.

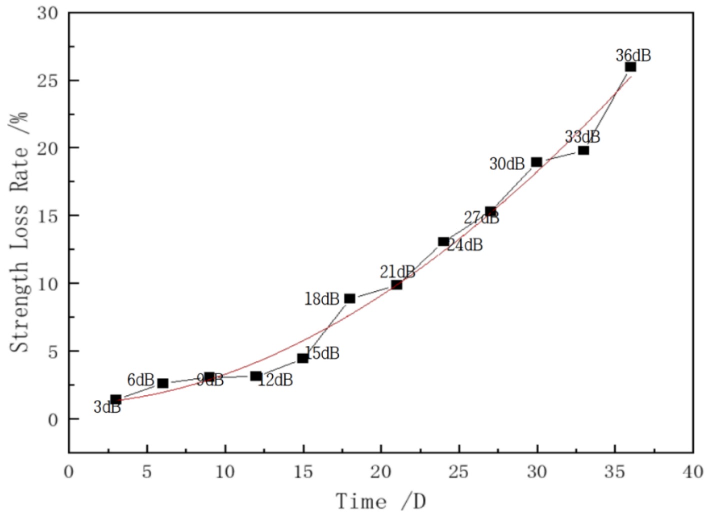


Fig. 9. Warp strength loss rate curve of black stock fabric as a function of the water immersion time, along with the fitted polynomial

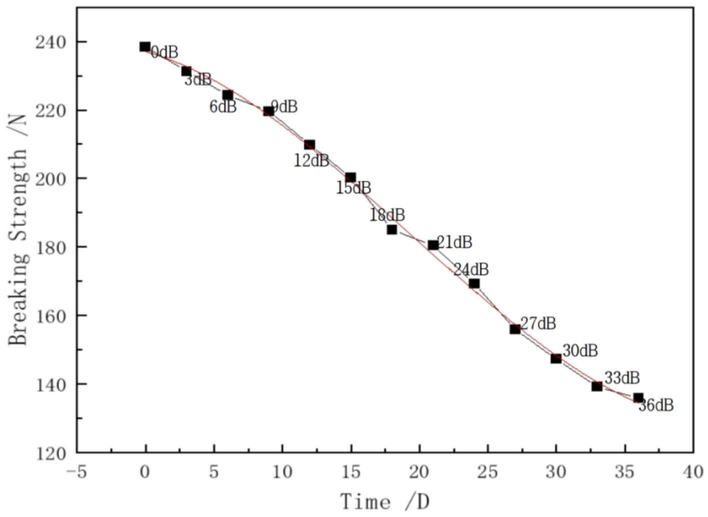


Fig. 10. Weft-breaking strength curve of black stock fabric as a function of the water immersion time, along with the fitted polynomial

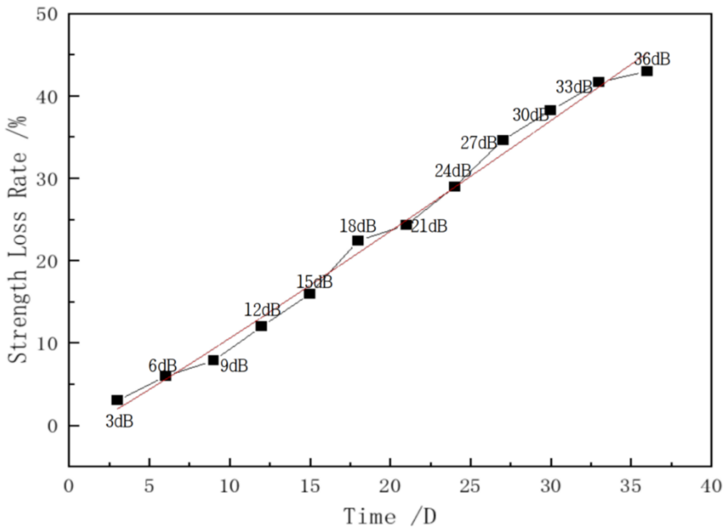


Fig. 11. Weft strength loss rate curve of black stock fabric as a function of the water immersion time, along with the fitted polynomial

Item	Value
Equation	y = a + b*x^c
a	-1.30967 ± 1.99386
b	1.02445 ± 0.4266
c	1.06488 ± 0.10863
R Squared (COD)	0.9921

Table 10. Variation equation of the weft strength loss rate of black stock fabric with the water immersion time

Table 11 is a quick reference table for the strength loss rate of cotton inventory fabrics after water immersion. This reference table can be used to quickly determine the strength key node times for these two types of fabrics. However, it is important to note that the estimated times may differ for other colored stock fabrics. Typically, the closer the color of the cotton stock fabric is to natural-colored fabric, the closer the estimated value will be to that of natural-colored fabric, while the closer the color is to black, the closer the estimated value will be to that of black fabric.

The visual characteristics of the cotton stock fabric following immersion in water can be observed in Table 12. The SEM images indicate that there were no noteworthy flaws in the structure of the control sample before it was immersed. With an increase in soaking time, the surface yarns gradually loosen, the fibers expand, and the cross-section enlarges. Additionally, a small amount of pulp and impurities on the fibers swell and adhere to the fiber surface after being soaked in water, which becomes more evident after six days of immersion. After 18 days of immersion, the residual pulp and impurities on the cotton stock fabric begin to aggregate and adhere to the fiber surface. By the 21st day, the loosening of the yarn fibers becomes more prominent. Finally, after approximately 27 days of immersion, the looseness of the fibers around the yarn reaches its peak before beginning to disintegrate entirely after 30 days.

Item	Loss rate	Natural color stock fabric (Time/D)		Black color stock fabric (Time/D)	
		After water immersion		After water immersion	
		Warp	Weft	Warp	Weft
Time /D	5%	13	3	14	6
	10%	23	4	21	10
	15%	30	5	27	13
	20%	35	7	32	17
	25%	40	9	36	21
	30%	44	13	40	25
	35%	48	17	43	29
	40%	52	24	46	32
	45%	55	33	50	36
	50%	58	45	52	40

Table 11. Quick reference table of strength loss rate node parameters for cotton stock fabric after water immersion

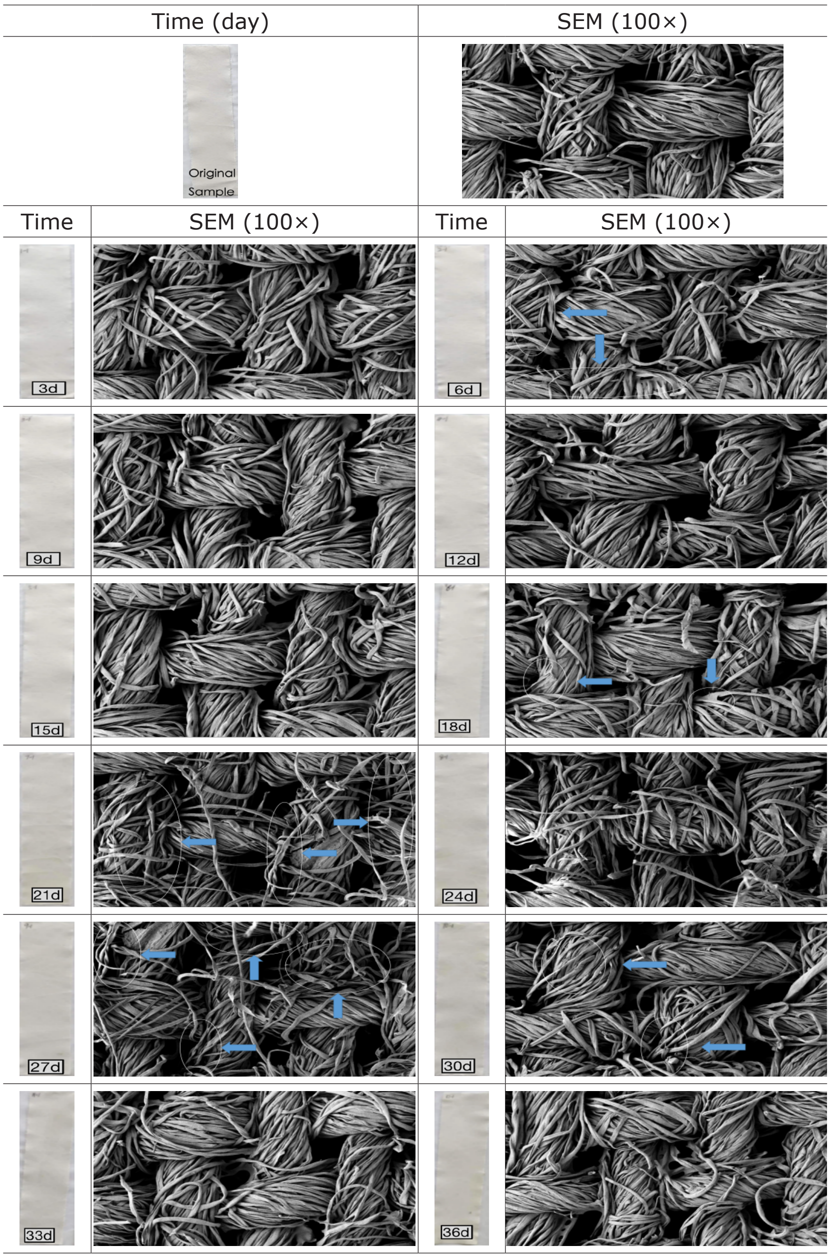


Table 12. Surface appearance of cotton stock fabric after immersion in water

5. Conclusions

Based on the analysis of Tables and in conjunction with the other experiments conducted in this study, the following conclusions can be drawn:

The physical properties of the stock fabric change noticeably after immersion in water, with the strength loss rate, color, and luster all significantly affected by the soaking time. Both natural-colored and black stock fabric experience a significant reduction in warp and weft strength after immersion, with the largest reduction observed in black stock fabric. Additionally, the color and luster of both fabrics become lighter, with the most significant changes observed in natural-colored stock fabric.

For natural-colored cotton stock fabric, the strength loss reaches 50% after approximately 45 days (or 1080 hours) of water immersion and storage. For black-colored cotton stock fabric, the strength loss reaches 50% after about 40 days (or 960 hours) of water immersion and storage. Generally, when the strength loss exceeds 50%, the fabric loses its upcycling value. Therefore, it is recommended to upcycle the fabric before reaching this time node and consider discontinuing upcycling beyond this time node.

Funding

This paper was fifinancially supported by Science and Technology Research Project of Jiangxi Provincial Education Department (GJJ2202802; GJJ202417)

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