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Dyeable electroconductive cotton wrapped CNT yarn for multifunctional textiles

Ke Jia[1], Wei Chen[2], Jianing Wang[1], Fujun Xu[2], and Wei Liu[1,*]

[1] *School of Textiles and Fashion, Shanghai University of Engineering Science, Shanghai 201620, People's Republic of China*
[2] *Key Laboratory of Textile Science and Technology, Ministry of Education, College of Textiles, Donghua University, Shanghai 201620, People's Republic of China*

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ABSTRACT

Conductive fiber plays increasingly important role in the field of multifunctional textile and smart clothing for the signal/power transmission, electrothermal function and so on. However, their major bottle necks are rigid, undyeable and limited durability. In this study, we manufactured a dyeable, washable and flexible conductive yarn by wrapping cotton roving fiber (wrapped fiber) on the surface of Carbon Nanotube (CNT) fiber (core yarn) and twisting them together by core-spun yarn spinning technique, named as cotton wrapped CNT yarn (CWC yarn). The appearance and flexibility of the CWC yarn are similar with the cotton yarn, but showing excellent conductivities of 100 Ω/cm, (undyed CWC yarn) and 50 Ω/cm (dyed CWC yarn). The electrothermal temperature of the CWC yarn with length of 5 cm reached 70 °C with applied voltage of 20 V, which was even higher than that of the pristine CNT yarn (60 °C). Furthermore, its electrical and electrothermal property changed slightly after being loaded, bent, knotted, fold-released (100 cycles) and washed, showing excellent durability. In addition, the electrochromatically dyed CWC yarn after weaving or embroidering into fabrics displayed changed colors with the various applied voltages. This work demonstrated a simple and referential method to design dyeable and washable multifunctional yarns for wearable applications.

Introduction

Wearable devices of intelligent textiles have been widely concerned and studied for their friendly interface with human body as well as various functions they provide. These devices are widely used as strain sensors [1–3], electronic skins [4], health monitoring systems [5, 6], super capacitors [7, 8] and so forth. As an important part of the wearable device, conductive fiber is critical to connect the functional elements together to supply the

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Address correspondence to E-mail: wliu@sues.edu.cn

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electrical power or transmit signal. Among the conductive fibers, carbon-based conductive fibers are being considered as promising candidates for their remarkable mechanical, electrical, thermal and optical properties [9, 10]. Some scholars dispersed CNT or graphene on the surface of yarns or fabrics by impregnation method to obtain flexible conductive textiles [11–13]. However, the self-entanglement and aggregation hinder the uniform dispersion of the CNTs in the aqueous solution, resulting in limited conductivity [14]. Moreover, the exposure of the CNTs to the surface of the substrate textiles causes the poor dyeability, durability and washability.

In recent decades, the aerogel-spun CNT yarn fabricated by floating catalyst chemical vapor deposition (FCCVD) shows a variety of advantages of high tensile strength, extraordinary structural flexibility, high electrical conductivity and outstanding corrosion/oxidation resistivity [15, 16], which makes it ideal for wearable electronics. For examples, Ma et al. [17] produced core/sheath structured highly sensitive strain yarn sensor by partially compositing CNT yarn with epoxy/acetone polymer solution to detect the tiny deformation of human skin. Wu et al. [9] manufactured a super elastic and electroconductive fiber by wrapping a flexible and conductive carbon nanotube/polydimethylsiloxane composite yarn onto a polyester filament for stretchable wearable electronics. Furthermore, over-twisted CNT fibers showed excellent stretching fatigue property and stable conductivity, that can be applied as stretchable conductor, actuator, even artificial muscle [18, 19]. After the CNT fibers/yarns were physically modified by annealing [20], cyclic stretching [21, 22], capillary force induced condensing [23] or chemically modified by acid treatment [24], plasma treatment [25], doping methods [26], its mechanical and electrical properties can be further enhanced. However, the intrinsically black color and undyeable inert surface limits the aesthetics design and practical applications.

In this study, a conductive yarn, named cotton wrapped CNT yarn (CWC yarn), was made by wrapping the cotton fiber on the surface of CNT yarn and twisting together. Its electrical, mechanical and thermal properties were characterized. In addition, the weaving property, dyeing property and electrochromic property of the CWC yarn were investigated. The CWC yarn embedded multifunctional fabric was also demonstrated as well.

Experimental

Materials

Pristine CNT yarns, as shown in Fig. 1a and b, with diameter around 50 μm were provided by Suzhou Jiedi Nano Technology Co., Ltd. The CNT yarn was spun directly from the chemical vapor deposition (CVD) synthesis zone of a furnace using a liquid source of carbon and an iron nano-catalyst [27, 28]. Other materials include pure cotton roving (3 Nm, Changzhou yanghu shuntian textile Co., Ltd), dyestuff (Red, yellow, green; Jinan yuanbaolai Chemical Technology Co., Ltd), Polyurethane (Dongguan BOGAO Chemical Co., Ltd), thermochromic inks (40 °C for the conversion temperature, colorless to green, Shenzhen Oriental Color Technology Co., Ltd) and conductive silver paste (Kunshan Chuang Wei Lvyuan Electronics Co., Ltd) were purchased from the commercial market.

Characterizations

The optical picture of the surface morphology was tested by SLR camera (SONY ILCA-77M2). The optical microscope and SEM image of the cross section were tested by optical microscope (GP-300C, Kunshan Gaopin Precision Instrument Co., Ltd) and scanning electron microscope (JEOL JSM-6490 LV). The tensile properties were tested by tensile instrument (XS(08)XT-3, Shanghai xusai Instrument Co., Ltd).

The resistance was tested by the resistance tester (keysight 34450A, Agilent Technologies Co., Ltd). The E-heating performance was tested by the infrared thermal image devices (S/N225, Shanghai Reimage Technology Co., Ltd), which powered by the DC power source (DP831A, Beijing Puyuan Jingdian Technology Co., Ltd).

Results and discussion

Fabrication and structure

Figure 2a showed the schematic of CWC yarn preparation process. Pure cotton roving was introduced into the compact spinning system at first. As following, the CNT yarn was introduced into the wrapping and twisting zone between the front roller

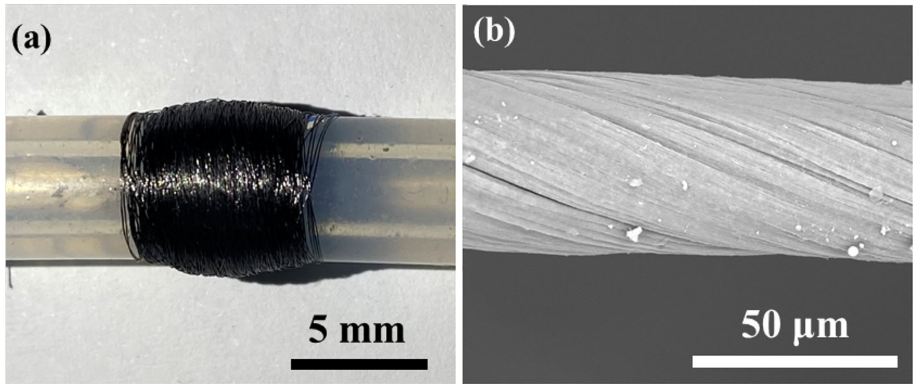

Figure 1 **a** Optical picture and **b** SEM image of the CNT yarn.

and compressed apron. In this way, the CNT yarn was tightly wrapped by the cotton fibers and thus CWC yarn was obtained. As shown in Fig. 2b and c, the optical figure and its amplified picture showed the cotton fibers on the outer surface of CWC yarn formed a uniform spiral wrapped structure. The CWC yarn showed an average diameter of about 0.7 mm, which was suitable for weaving processing and wearable applications. Its cross-sectional view as shown in Fig. 2d and e showed that the inner CNT yarn with a diameter of ~ 50 μm was tightly surrounded by cotton fibers. Therefore, cotton yarn-like appearance provides CWC yarn great potentials to the wearable applications.

Electrical and electrothermal performance

Figure 3 showed the electrical and electrothermal performance of CNT yarn and CWC yarn with length of 5 cm. As shown in Fig. 3a, the E-heating temperatures of both yarns remarkably increased with the applied voltages rising from 5 V to 22.5 V. As applied by the same voltage, the CWC yarn showed higher E-heating temperatures than the CNT yarn. The highest E-heating temperature of the CWC yarn reached 81.3 °C at 22.5 V, which is around 10 °C higher than that of the CNT yarn. This is because the wrapped cotton fiber provided a thermal insulation layer on the CNT yarn, which hindered the heat dissipation and enhanced surface temperature. The infrared images as shown in Fig. 3b exhibited the uniform temperature distribution. The temperatures of the CWC yarn raised immediately in a few seconds and then reached maximum values as shown in Fig. 3c, showing a quick response to the applied voltages. When the power supply was cut off, the CWC yarn cooled down rapidly to the ambient temperature.

Figure 3d showed the real-time changing temperature of CWC yarn as the applied voltage switching

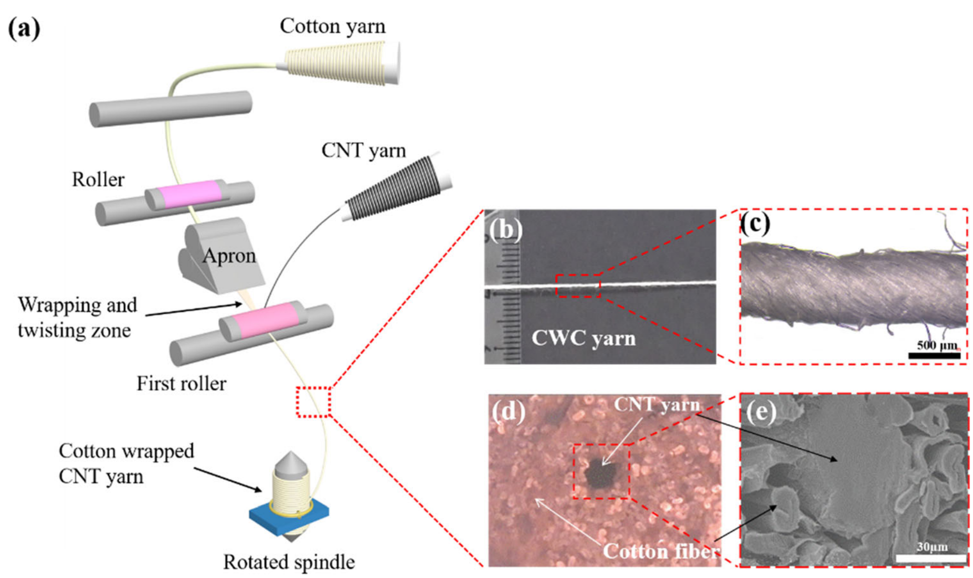

Figure 2 **a** Schematic of CWC yarn preparation process. **b** Optical microscope and **c** its amplification picture of the appearance of CWC yarn. **d** Optical microscope and **e** SEM image of the cross section of CWC yarn.

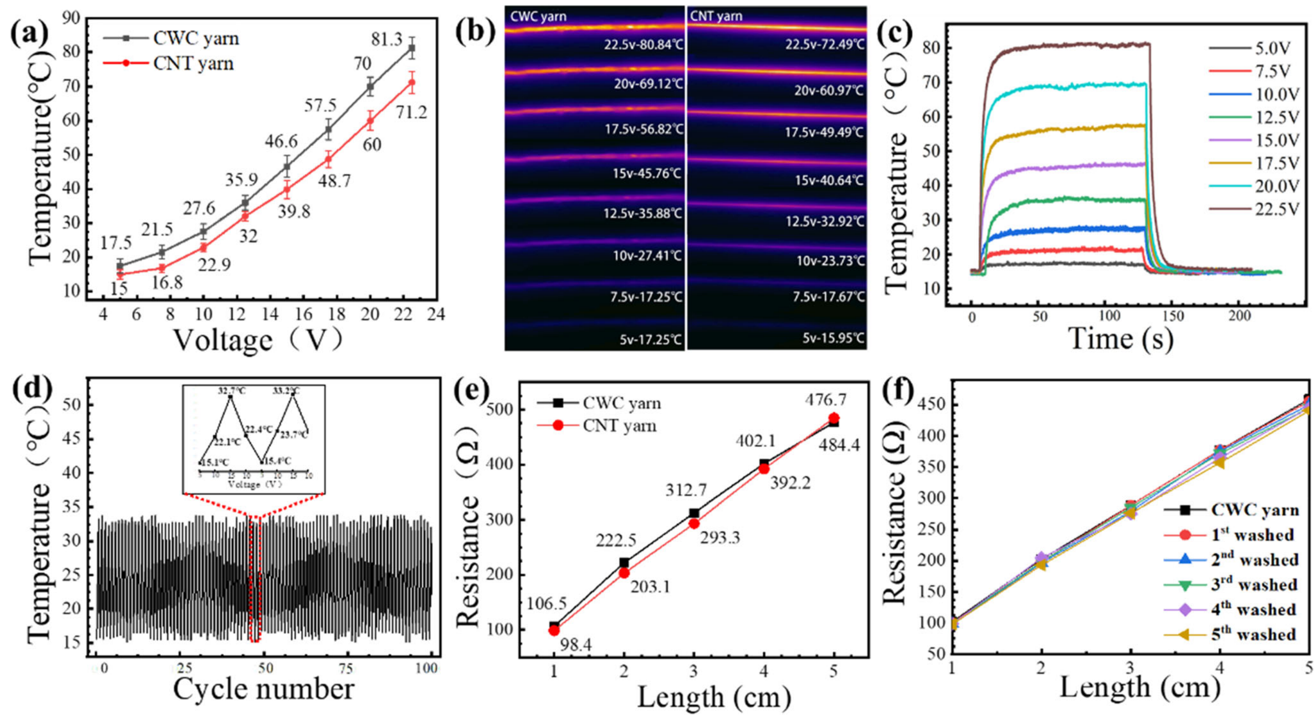

Figure 3 **a** Electrothermal temperature as a function of applied voltage. **b** Infrared images of 5 cm-long CNT and CWC yarn with various applied voltage. **c** Electrothermal temperature curves of CWC yarn as a function of time. **d** Electrothermal temperature curve of CWC yarn with the switched voltage from 5 to 15 V. **e** Electrical resistance of CNT and CWC yarn with various lengths and **f** after five times washing.

from 5 to 15 V for 100 cycles. The temperatures of the yarn were stable at 5 V (~ 29 °C) and 15 V (~ 46 °C), indicating its repeatable and reliable electrothermal property. As shown in Fig. 3e, the electrical resistances of both CNT yarn and CWC yarn increased linearly from ~ 100 Ω to ~ 480 Ω with yarn length increased from 1 to 5 cm, which indicates the core CNT yarn in the wrapped yarn is straight and intact. To investigate the reliability of the CWC yarn, the yarn was washed for imitating the real wearable application. It was hand washed in a soap water solution with 4 g/L concentration at 40 °C for 5 min and dried at room temperature. As shown in Fig. 3f, after five repeated washing cycles, the resistance of the CWC yarn was slightly changed.

Mechanical properties

Figure 4a showed the load strain curve of both CNT and CWC yarn. Due to its limited diameter (~ 50 μm), the pure CNT yarn can only bear 0.25 N load. While the CWC yarn showed higher tensile breakage load (~ 7 N) due to the support of the wrapped cotton fibers. As shown in Fig. 4b, after 100 cycles of bending and releasing, the electrical resistance of the yarn was slightly changed. Furthermore, the uniform infrared images of the CWC yarn with bending and knotting was shown in Fig. 4c and d, indicating its excellent flexibility. Figure 4e showed that the CWC yarn possessed stable conductivity and kept a LED light lighting even under 200 g loading.

Electrothermal performance of the CWC yarn embedded fabric

The CWC yarn can be woven into a fabric. Figure 5a showed the CWC yarn was interlaced into a cotton fabric as weft yarn. Due to the cotton surface appearance and flexibility of the yarn, the fabric looks as same as a normal woven cotton fabric. With folding the fabric into different angles from 135° to 0° as shown in Fig. 5b, the variation of its resistance was lower than 8Ω (353 ~ 361 Ω). Due to the cotton fiber provides protecting outer layer for the CNT core yarn, the CWC yarn obtained good durability. Even after 100 folding–releasing cycles, the resistance still maintained around 360 Ω as shown in Fig. 5c. In addition, a single CWC yarn was embroidered into a

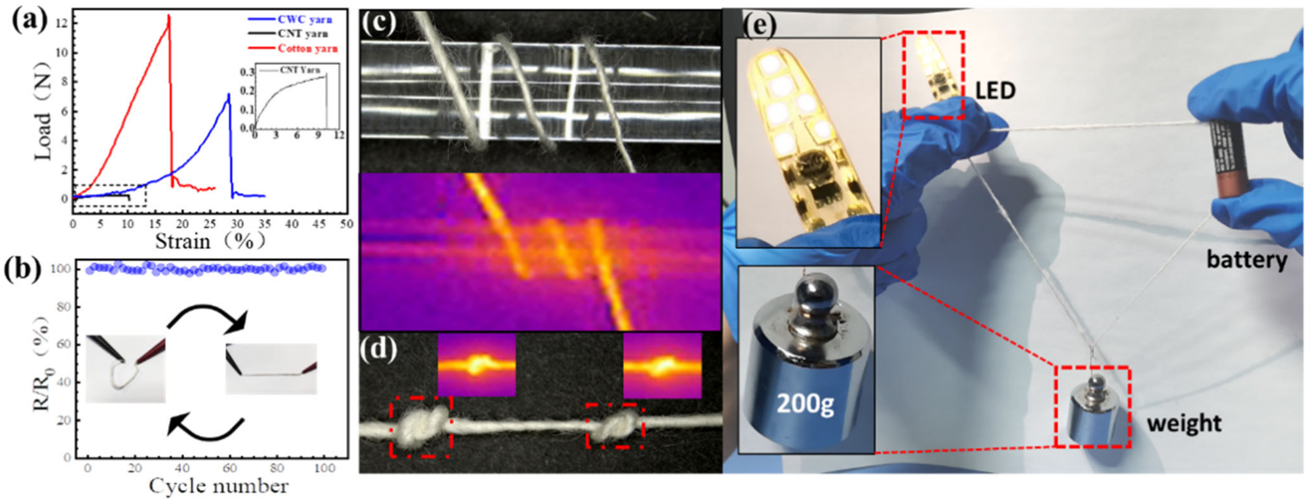

Figure 4 **a** Comparison of tensile properties of the CWC yarn, CNT yarn and cotton yarn. **b** Resistance changing ratios of the CWC yarn under 100 bending cycles. Optical and infrared images of the CWC yarn after multiple **c** bending and **d** knotting. **e** Demonstration of the conductive behavior of the CWC yarn under 200 g loading.

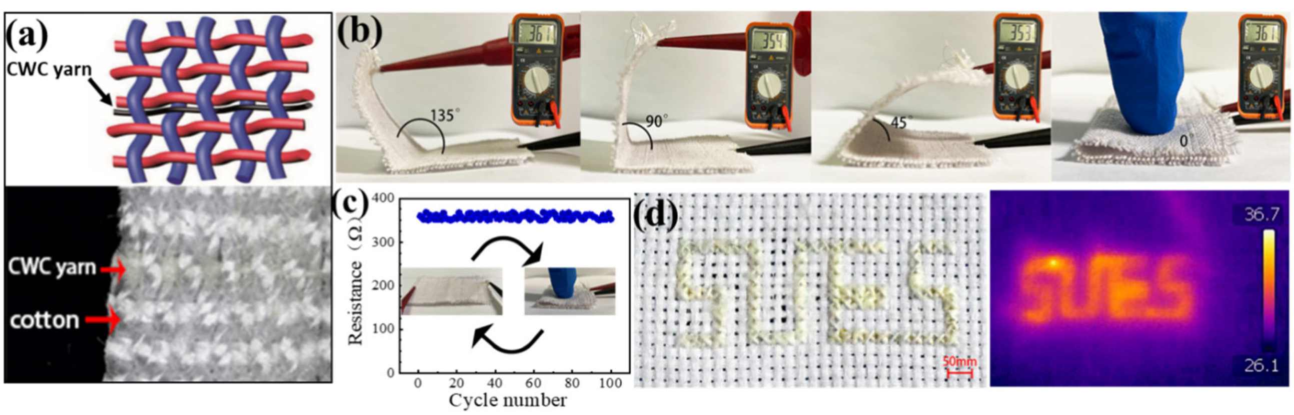

Figure 5 **a** Schematic diagram and physical diagram of the woven cotton fabric interlaced by CWC yarn. **b** CWC yarn embedded fabric folding into different angles. **c** Resistance of the CWC yarn in fabric with cyclic folding. **d** Optical picture and infrared images of the CWC yarn stitched pattern in cotton fabric.

cotton fabric with a pattern of "SUES". By connecting the two ends of the yarn to an electric power, the pattern can be E-heated with clear "SUES" letters showed in its infrared image in Fig. 5e.

Color changing performance of the CWC yarn embedded fabric

The CWC yarn has good dyeability that it can be dyed into different colors. As shown in Fig. 6, the CWC yarns were dyed into red, white, green and yellow colors by using the commercial dyes (Reactive dye) and then used as conductive wires to light LEDs. The dyed CWC yarn was also flexible and can be embroidered into cotton fabrics in Fig. 6b. Unexpectedly, as shown in Fig. 6c, the conductivity of dyed CWC yarn increased due to the core CNT yarn can be densified by ethanol in dye solution [29]. Additionally, after coating by the electrochromatic ink, the CWC yarn in its embedded fabric displayed obvious color changing from white to green with applied voltages increased from 5 to 15 V as shown in Fig. 6d. This is due to the temperature of CWC yarn enhanced from 28.5 to 57.9 °C as the voltage increased.

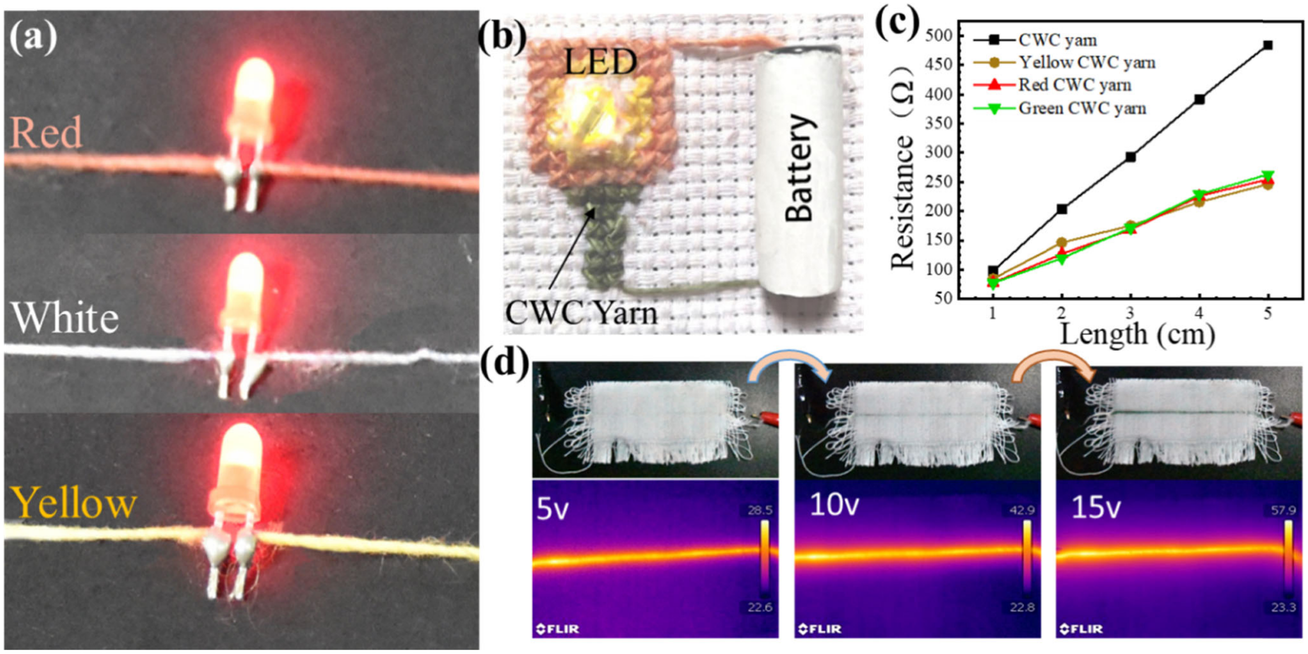

Figure 6 **a** Demonstration of the dyed CWC yarn as conductive wires. **b** Wearable electrical circuit with dyed CWC yarn. **c** Resistance of the dyed CWC yarn. **d** Optical and infrared images of the eletro-thermochromatic coated fabric under different voltages.

Conclusion

In this study, the CWC yarn was prepared by wrapping the cotton fiber on the CNT yarn via core-spun yarn spinning technique. The experimental results showed that the similar appearance, flexibility, washability, durability and dyeability with common cotton yarn, but excellent conductivity and electrothermal property over it. The CWC yarn showed good conductivity and electrothermal property after bending, loading, knotting, cyclic folding-releasing and repeated washing. Moreover, the CWC yarn can be easily dyed by commercial dye. After being woven or embroidered into cotton fabric, the dyed CWC yarn still exhibited excellent electrical and electrothermal property.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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