Nonwoven carbonized viscose mat for outstanding electromagnetic shielding, fast electrical heating and fire alarm

Xinghua Hong¹,²,³, Menghan Shi¹, Wei Sun¹, Hongfeng Lao¹, Junnan Qian¹ and Haibing Qiu¹,²

Abstract
Disposable face towel derived amorphous carbon prepared by annealing for broad and exacting applications in electromagnetic shielding, electrical heating, etc. This mat with 3D conductive network formed by nonwoven viscose fiber structure gives an outstanding electromagnetic shielding performance of 30 dB and 8161 dB/(g/cm²) at a thickness of 0.168 mm in the frequency range of 0.3–3.0 GHz. In addition, the as prepared mat presents excellent temperature & strain sensing with exceptional sensitivity (BS = 5.5%), and favorable flexibility (1000 bending cycles without fracture). Moreover, the mat provides well Joule heating performance, and the heating temperature can reach over 60°C in 32 seconds under 0.25 A current. More interestingly, the mat shows excellent fire alarm with a fast response (84 ms) and high operating temperature (>500°C). This
method provides a simple and low-cost new method for radiation protection, temperature detection, fire alarm and other fields.

**Keywords**
Carbonized viscose mat, recycling, electromagnetic shielding, electric heating, sensing

**Introduction**
Wearable smart textiles, strain sensors are widely used in electronic skin\(^1\)--\(^4\) and health monitoring,\(^5\)--\(^8\) and have a broad prospect. But at the same time, the electromagnetic radiation generated by electronic equipment will interfere with human health and instrument accuracy, affecting the normal operation of electronic equipment such as mobile phones, radars and medical instruments. Electromagnetic shielding materials can effectively shield electromagnetic waves through the reflection and absorption of electromagnetic waves.\(^9\) In addition, fast and safe temperature control are highly needed in extreme climates or health testing (fever, neurological disorders, etc.)\(^10\)--\(^12\) and high temperature warning.\(^12\) Therefore, a multifunctional flexible electronic smart textile that integrates strain & temperature sensing, electromagnetic shielding and electric heating performance can be designed to meet the demand.

Generally speaking, there are two ways to obtain textile based electromagnetic shielding materials. One is to prepare functional fibers for weaving,\(^13\) and the resulting fabrics can achieve electromagnetic shielding effect. For example, Zheng Ian Lin\(^14\) and others used polypropylene (PP)/multi-walled carbon nanotube (MWCNT) coated polyethylene terephthalate (PET) yarn to make conductive woven/knitted fabrics. However, the cost of this method is high, and it cannot be popularized on a large scale. Another method is to directly coat traditional textiles. This method is widely used. In previous reports, common coating materials include AgNWs,\(^15\) Mxene\(^16\) and graphene,\(^17\) but this method cannot guarantee the firmness of conductive materials on the surface of fabrics. Therefore, the invention provides a different method to carbonize cellulose nonwovens and realize electromagnetic shielding performance by using the internally formed conductive network. The process is simple and overcomes the above problems.

Cellulose is the most abundant biological material in nature. Cellulose fiber is widely used to prepare sensors. When subjected to simple heat treatment, these cellulose materials can be turned into biomass carbon materials to achieve excellent conductivity, making them suitable for conductive materials used in sensors. Weihong Zhou et al.\(^18\) Prepared a new Fe\(_3\)O\(_4\)/cellulose carbide micro nano hybrid microwave absorber with self-assembled porous structure by loading a simple process of hydrolyzing Fe\(^{3+}\) polymer, freeze-drying and annealing. Renewable biomass carbon material has attracted much attention in terms of its rich source, low cost and adjustable structure. Biomass carbon materials such as wood,\(^19,20\) bamboo,\(^21\) cotton,\(^22–24\) lotus leaf\(^25\) and water chestnut shell\(^26\) have been reported so far. Viscose fiber is a kind of renewable cellulose fiber, with good moisture absorption, softness and smoothness, is widely used in all kinds of textiles,
especially through the non-woven technology made of disposable products such as wet towels, face towels, resulting in inevitable waste. Every year, more than 40 million tons of waste textiles are produced all over the world. Therefore, from the perspective of environmental protection and economy, the recycling of textiles has become an urgent problem to be solved.\textsuperscript{27} Besides, viscose fiber has good flexibility, ion exchange capacity and biodegradability, and is widely used in textile and chemical industries.\textsuperscript{28} Nowadays, most of the research performed on viscose is done by modifying viscose with chemicals, in use of Ag/AgX (X = Cl, I) NPs,\textsuperscript{29} alginate,\textsuperscript{30,31} chitosan\textsuperscript{32} and metal nanoparticles.\textsuperscript{33} However, to the best of our knowledge, there are few reports on disposable viscose mat by annealing and utilizing up to now, which is of significance for recycling use of textile waste, waste management and circular economy.

Herein, the disposable viscose face towel was carbonized by annealing to form amorphous carbon mat with the concept of green environmental protection. Wherein, the amorphous carbon mat with 3D conductive network endows with outstanding electrical performances, including electrical conductivity of 42 S/m, electromagnetic shielding performance of 30 dB and 8161 dB/(g/cm\textsuperscript{2}), and the heating temperature can reach over 60\textdegree C in 32 seconds at 0.25 A current, further showing fast and stable Joule heating performance. In addition, the prepared mats have excellent temperature and strain sensing properties as well as good flexibility. More interestingly, this mat provides excellent fire alarm with a fast response (84 ms) and high operating temperature (>500\textdegree C). This carbonized viscose fabric made by simple preparation method has capacity in electromagnetic shielding, electric heating, temperature alarm and so on.

\section*{Materials and methods}

\textbf{Preparation of Carbonized face towel}

Disposable face towel (JM102, 20×20 cm, 230 g) was purchased from Zhejiang Keer Cosmetics Co., LTD, China. The preparation process of carbonized viscose fabric is shown in \textbf{Figure 1}. First, put the dried sample into the tubular furnace (OTF-1200X). In order to compare the performance of the sample under different carbonization temperatures, raise the temperature to 300\textdegree C, 600\textdegree C and 900\textdegree C respectively under the protection of nitrogen, annealing at the heating rate of 5\textdegree C/min, N2 inlet rate of 2.5 ml/min, carbonize at the corresponding temperature for 2 h, and cool at room temperature. The prepared samples were named CVM-300, CVM-600 and CVM-900, respectively. To compare the samples before and after carbonization, the original disposable face towel without carbonization was named CVM-0.

\textbf{Characterization}

The morphology of the carbonized viscose fabrics was characterized using a scanning electron microscope (SEM, Sigma 300, Zeiss, Germany); the functional group of material was analyzed by a Fourier infrared spectroscopy (FT-IR, Nicolet Fourier infrared spectrometer, Thermoelectric Negoly Company) in the spectral range of 500–4000 cm\textsuperscript{-1};
the X-ray photoelectron spectra of the samples were obtained using an X-ray photoelectron spectrometer (XPS, K-alpha, Thermo Scientific, USA); the resistance of the samples was measured using a resistance tester (DMM 6500. Tektronix Co, Ltd., China). The electromagnetic shielding effectiveness of the samples was measured by a fabric anti-electromagnetic radiation performance tester (EMI SE, FY800, Wenzhou Fangyuan Instrument Co., Ltd, China); a self-assembled dynamic resistance tester was used to record the resistance changes of the samples under different strains, including resistance tester (DMM 6500. Tektronix Co, Ltd., China) and mechanical test system (EJA SERIES, Thwing-Albert Co., USA); an infrared thermal imaging camera (InfraTec, FLIR System, Germany) was used to record the temperature distribution and thermal images of the samples, and the applied constant current was provided by a three-way programmable DC power supply (IT6322, ITech, USA).

### Result and discussion

Figure 2 shows the basic morphology, composition and structure of the carbonized viscose at different carbonization temperatures. As Figures 2(a)-(d) shown, the impurities and grooves on the fiber tow surface gradually decrease with the increase of carbonization temperature and the micro voids can be observed on the surface of single CVM-900 fiber. Figure 2(e) shows the infrared spectra of CVM-0, CVM-300, CVM-600 and CVM-900, the absorption peaks at 3351 cm$^{-1}$ (corresponding to hydroxyl group of -OH) and 995 cm$^{-1}$ (corresponding to -CH) gradually decrease with the increase of temperature. Which is mainly ascribed to that the carbonization process of cellulose viscose fiber is a pyrolysis process, with the increase of carbonization temperature, the hydroxyl group
Figure 2. SEM images of (a) Pristine, (b) CVM-300, (c) CVM-600 and (d) CVM-900. (e) FTIR spectra of Pristine, CVM-300, CVM-600 and CVM-900. (f)-(h) XPS spectra, C$_{1s}$ spectra and O$_{1s}$ spectra of CVM-300, CVM-600 and CVM-900. (i) Permeability test of CVM-900.
(–OH) in the viscose is destroyed and gradually change to carbon mat structure, while the decrease of R1CH=CH2 was due to the small amount of olefins contained in the production of disposable washcloths during the carbonization process gradually volatilized with the increase of carbonization temperature. The polar functional groups that may be contained in disposable face towels have been removed during the carbonization process, and they are chemically inert and harmless to human body. Moreover, carbonated CVM-900 has good air permeability and will not affect its function as an intelligent wear-resistant textile (Figure 2(i)). The XPS spectra of the carbonized samples are shown in Figure 2(f), where the C1s and O1s peaks can be observed at 284 eV and 533 eV, respectively. The C1s and O1s XPS spectra of the carbonized samples were peak fitted and the results are shown in Figures 3(g) and (h). The C1s spectra of the three fabric samples can be fitted by three sub-peaks of C–C, C–O and O=C–O bonds with centers of 284.7 eV, 286.5 eV and 288.2 eV, respectively. The O1s spectrum can be fitted by one peak of the C–O–H bond, centered at 532.6 eV, indicating that as the carbonization temperature increases, the C=O, hydroxyl and hydrogen bonds in the cellulose molecule are destroyed, water molecules and CO2 are precipitated, and the graphitization of the fabric is increased. To sum up, the increased graphitization incorporates into nonwoven network structure provides a 3D conductive network of the internal electron transfer, which improves the electromagnetic shielding, electrical heating, and fire alarm properties of CVM.

Figure 3(a) shows the electromagnetic shielding mechanism of carbonized viscose. When the incident electromagnetic wave collides with the carbonized viscose surface, the movable carriers on the material surface interact with the incident electromagnetic wave, so that part of the incident electromagnetic wave will be reflected. When the remaining electromagnetic wave propagates into the sample, part of the electromagnetic wave will be absorbed due to ohmic loss and polarization loss. Also, the porous structure of the nonwoven material, repeated reflections and scattering further lead to absorption of electromagnetic waves, so that only a small fraction of the electromagnetic waves pass through the fabric.

Figure 3(b) shows the electromagnetic shielding efficiency (SE) of three samples with different carbonization degrees. The electromagnetic shielding ability of CVM-300 and CVM-600 remains unchanged, basically the same as CVM-0, while the electromagnetic shielding ability of CVM-900 is significantly improved up to 30 dB. This is mainly ascribed to that in the early stage of carbonization, the pyrolysis of cellulose is mainly controlled by dehydration and depolymerization. After carbonization, the cellulose presents a porous structure, which is evenly distributed in the whole sample. Many carbon nanofibers are wrapped around the mesopores, which can provide electron transfer paths and form conductive networks, significantly improving the conductivity of carbon electrodes. At 600°C, the cellulose bundles still maintain a fairly crystalline structure. With the increase of temperature, this crystal shows signs of instability, because some cellulose chains are misplaced from their original positions, and the further increase of temperature leads to the gradual decomposition of fiber bundles. At 900°C, the main part of the beam has been depolymerized into various types of segments, so the electromagnetic shielding at 600°C is quite different from that at 900°C.
As shown in Figure 3(c), the SE of CVM-900 becomes stronger when the number of sample layers increases. When the CVM-900 is four layers, the thickness is 0.672 mm, the electromagnetic shielding efficiency can reach 52 dB, and the minimum is 37 dB, is three layers, the thickness is 0.507 mm, the minimum electromagnetic shielding efficiency is 33 dB, meeting the industrial electromagnetic shielding fabric and microwave radiation anti-chemical suit class B standard based on standard of GB/T 23463-2009.

Table 1 shows the comparison of the EMI shielding performance of CVM with the reported samples of the X-band. The SET/Grammage values of CVM are competitive among all samples.

Figures 3(d)-(e) shows the linear relationship between thickness/SE vs. thickness, grammage/SE vs. grammage for CVM-900. The reciprocal of the slope gives values of SE, namely 71 dB and 60 dB. The main mechanism is that the electromagnetic shielding does not reach saturation reflection when the thickness and grammage of the prepared carbonized viscose is low mass and low bulk density. Overall, the linear trend of

![Figure 3](image-url)
grammage/SE vs. grammage of the carbonized material is obvious. This trend means that a smaller amount of CVM makes more efficient in providing shield of the microwave.

The EMI SE of material is closely related to the thickness and grammage of the sample. To study the influence of sample thickness on the electromagnetic shielding performance, CVM-900 was stacked together for electromagnetic shielding test. Figure 3(f) provides the SE, SE/thickness and SE/grammage of the CVM under different temperatures, and Figure 3(g) shows the radar plots of SE, SE/thickness and SE/grammage of CVM-900 at different layers in X-band. The EMI SE increases from 0.45 dB to 17.14 dB with the annealing temperature increases from 300°C to 900°C, which is caused by the degree of carbonization of the viscose. And EMI SE increases from 17.1 dB to 37.8 dB with the increase of thickness. Obviously, SE/grammage increases with the increase of carbonization temperature and thickness, from 55 dB/(g/cm²) (300°C, 0.266 mm) to 8161 dB/(g/cm²) (900°C, 0.168 mm), mainly owing to mass and thickness are the main factors that determine the electromagnetic shielding performance of the material within skin depth.39,40

Figures 4(b)-(c) shows the ΔR/R₀ curves of the CVM-600 and CVM-900 fabric sensors response to different pressure actions. The strain of the fabric is generally sensed by the change in resistance ΔR/R₀ in response to the strain. The relative resistance change of CVM-600 under the same pressure is larger than that of CVM-900, indicating that the contact resistance of CVM-600 plays a greater role than that of CVM-900. And the relative resistance change of CVM fabric sensor increases with the increase of pressure.

Figure 4(d)-(e) shows the resistance changes of CVM-600 and CVM-900 fabric sensors for 100 and 1000 bending cycles, with the increase of dynamic bending cycles, the resistivity tends to increase, where the fluctuation of CVM-600 is larger.

Table 1. Comparison of electromagnetic interference shielding performance of CVM and competitive materials in X-band (Bold values shows the best effect among the references in the table).

| Materials     | Structure   | Temperature (°C) | EMI SE (dB) | Thickness (mm) | SEₓ/Thickness (dB/mm) | SEₓ/Grammage (dB/(g/cm²)) | Ref     |
|---------------|-------------|-----------------|-------------|----------------|-----------------------|---------------------------|---------|
| Mxene- FRV/SA | Knitting    |                 | 20∼60       |                |                       |                           | 41      |
| Wood-pulp     | Woven       | 2000            | 44.5        | 0.3            |                       |                           | 42      |
| SC-Co-G       | Nonwovens   | 900             | 55          |                |                       |                           | 43      |
| Toilet papers | Nonwovens   | 1000            | 30∼40       | 1.0            |                       |                           | 44      |
| CNF-Bamboo    | Film        | 1100            | 23          | 1.7            |                       |                           | 45      |
| PCB-CB/CCT    | Knitting    | 1100            | 43          | 0.4            | 107.3                 | 1619                      | 46      |
| Ni-Cotton     | Woven       | 800             | 20−25       | 0.7            | 32.9                  |                           | 47      |
| CVM-300       | Nonwovens   | 300             | 0−2         | 0.3            | 0.8                   | 55                        | This work |
| CVM-600       | Nonwovens   | 600             | 0−2         | 0.2            | 2.3                   | 100                       | This work |
| CVM-900       | Nonwovens   | 900             | 10−35       | 0.2            | 86.6                  | 8161                      | This work |

Journal of Industrial Textiles
In order to express the sensitivity of bending sensing, BS (bending sensitivity) is defined. This value represents the change of resistance per unit bending angle, so the greater the value, the higher the sensitivity. The calculation formula is defined in equation (1):

$$BS = \frac{\Delta R}{R_0 \sin \theta} \times 100\%$$  \hspace{1cm} (1)$$

Where, $\Delta R$ is the resistance change ($\Omega$), $R_0$ is the initial resistance of the sensor ($\Omega$), and $\theta$ is the equivalent bending angle.

From the figure, it can be calculated that the BS value of CVM-900 is 5.5%. The relatively low sensitivity of CVM-900 is ascribed to the fast recovery of 3D conductive
network contact points. Therefore, the sensitivity of CVM-900 is lower than that of prior works.\textsuperscript{48,49} The relative resistance change of CVM-900 is smaller than that of CVM-600 (shown in Figure 4(g)), which is only 2.6\% and has better stability.

Figure 4(f) is a schematic diagram of the principle of resistance change of the fabric sensor under bending and releasing. When the fabric is bent, the contact points between the fibers become less, and the corresponding fabric resistance increases. As the bending cycles increases, few permanent displacements or damage has occurred in nonwoven fabric, leading to an increase in its resistance compared with the initial state. These results vividly illustrate the better durability of the carbonized viscose material and expect more stable performance in future studies.

Figure 5(a)-(b) shows the change of CVM-600 and CVM-900 resistance with data acquisition frequency. According to Formula 1, when the data acquisition frequency is 0.02s, the BS values of CVM-900 and CVM-600 are 5.5\% and 14.3\% respectively, and when the data acquisition frequency is 0.68s, the BS values of cvm-900 and cvm-600 are 4.4\% and 6.2\% respectively. When the acquisition frequency decreases, the corresponding sensitivity of the sensor will also decrease, which indicates that the data acquisition frequency has a negative effect on $\Delta R/R_0$ has a great impact on the results. Which may lead to errors during experimental analysis, so the selection of data acquisition frequency is important for the sensitivity, gauge factor (GF), and response time of the sensor. Figure 5(c) shows the correspondence between the fabric $\Delta R/R_0$, the deformation,
and deformation speed in the cyclic process, which can be divided into four stages. 
(i) Sample bending deformation and bending speed gradually accelerated, at the same
time, the fiber began to slip between the contact points become less, the resistance began
to rise. (ii) Bending speed gradually decreases until it stops, the fiber bending deformation
to the maximum, the contact point begins to slip, the resistance gradually increases and
returns to a small section. (iii) Bending deformation began to recover and gradually
accelerate, the contact point decreases, the resistance increases slightly. (iv) Bending
deformation is completely restored, the contact point continues to return, and the re-
sistance decreases sharply. In summary, the resistance change of the textile sensor mainly
occurs to the beginning and end of the deformation, mainly related to the structure of the
sensor and deformation.

Figure 6(a) shows the schematic diagram of the electrothermal test setup, and
Figure 6(b) is thermal imaging of CVM-900, indicating that the CVM-900 converts
electrical energy into thermal energy at the applied current, showing a relatively uniform
temperature distribution image. Figure 6(c) represents the equilibrium temperatures of the
CVM-900 are 21.3°C, 24.8°C, 32.8°C, 47.2°C and 64.6°C at different constant currents
of 0.05 A, 0.10 A, 0.15 A, 0.20 A and 0.25 A, respectively, and the temperature rise rate of
the CVM-900 is stable at about 3 s in low current and at about 32 s in high current.50 As
Figure 6(d) shown, the applied current increases from 0.05 A to 0.25 A, the which results
in relative resistance $\Delta R/R_0$ of CVM-900 changes from $-1.14\%$ to $-6.16\%$. After
turning off the constant current, the relative resistance of the material return to the initial
state. Figure 6(e) shows the temperature variation of CVM-900 within 4 min under
different currents, indicating the well electrical heating stability. Figure 6(f) shows
successive temperature evolution of CVM-900 under different currents. The steady-state
temperature of CVM-900 under different currents is shown in Figure 6(g), and the
equilibrium temperature is roughly linear with the square of the current.

Since electric energy cannot be completely converted into heat energy in the process of
electric heating, under the action of applied voltage, the steady-state maximum tem-
perature of carbon felt remains unchanged. According to the law of conservation of
energy, the thermal gain of electric power is equal to the heat loss of radiation and
convection51, $hr+c$ is defined to represent the electrothermal conversion efficiency. The
smaller the value is, the higher the electrothermal conversion efficiency is, which can be
calculated according to equation (1)52

$$hr+c = \frac{V \cdot I_c}{T_m - T_0}$$  \hspace{1cm} (2)

Where, $hr+c$ is the electrothermal conversion efficiency, $I_c$ is the balance current, $V$ is the
applied voltage, $T_0$ and $T_m$ are the initial temperature and the maximum balance tem-
perature respectively. According to this formula, the $hr+c$ value of CVM-900 is obtained,
as shown in Figure 6(h). With the increase of voltage, the electrothermal conversion
efficiency is lower, but after the voltage reaches 9 V, the electrothermal conversion
efficiency gradually increases.
Figure 7 shows the temperature sensing performance of CVM fabric. As Figure 7(a) shown, when molecular thermal motion increases, the average speed of microscopic particle accelerates, followed by the external bound electrons transfer into free electrons, resulting in resistance decreases with the temperature increasing. Figure 7(b) shows that the relative resistance of CVM-900 changes linearly with oven temperature, and its resistance temperature coefficient is $-0.665\%/{}^\circ\text{C}$, also indicating that the resistance change of CVM-900 is caused by temperature change.

Figure 7(c) shows the curves of temperature and corresponding $\Delta R/R_0$ vs. time for CVM-900 at 0.25 A. The fire alarm can be achieved based on the change of the relative resistance of CVM-600 and CVM-900 fabrics as Figure 7(d) shown. The red color area indicates that the relative resistance of the fabric employed obvious variations of $-90\%$ (CVM-600) and $-20\%$ (CVM-900) within 79 ms and 84 ms when the flame operates to
contact CVM, they have short response time and high sensitivity. This is due to the fact that flames are electrically conductive plasma. Therefore, the conductivity of the sample is instantly improved. After the flame move out, the CVM-600 breaks and the resistance rises to infinite immediately. More interestingly, the CVM-900 was completely carbonized and did not burn, when the flame left, the resistance returned to the original state.
in 103 ms, indicating the capability of multiple reuses. In sum up, CVM-600 and CVM-900 can be used for fire alarm, and CVM-900 can be reused to reduce the cost. Figure 7(e) shows the repeatability and stability of CVM-900 for fire alarm. When CVM-900 is placed on the alcohol lamp, its resistance will immediately decrease by to 20%, and the resistance will recover after the flame leaves. After repeated several times, it is found that the resistance change is basically stable, indicating this CVM can be recycled for fire alarm as an easily prepared, cost-effective and valuable material.

Figure 8. (a) Schematic diagram of resistance measurement of CVM in-plane direction. (b) Equivalent circuit model of the CVM. (c) Plot of resistance vs. thickness for CVM-600 and (d) CVM-900. A schematic diagram of the resistance R versus thickness d used to determine the contact resistance R_i of the specimen is placed internally. (e) Electrical conductivity of CVM-600, CVM-900 in plane direction. (f) Contact resistance R_i of CVM-600 and CVM-900.
Figure 8(a) is the schematic diagram for measuring resistance of different lengths of CVM. Figure 8(b) shows the equivalent circuit model of CVM, which is used to decouple the contact resistance $R_i$. Wherein, the contact interface resistance is $R_i$, CVM self-body resistance is $R_a$, and gap resistance is $R_b$. $^{35}$CVM in the circuit is in parallel with the air in the pores between the internal fibers, which is then connected in series with two electrical contacts. In order to explore the interface effect of CVM, resistance values of different lengths were tested, the results are shown in Figures 8(c)-(d). The resistance gives a linear relationship with thickness. Based on the equivalent circuit model (Figure 8(b)) and fitting results, the self-body conductivity and contact interfaces resistance $R_i$ (half intercept) between CVM and copper electrode can be extracted. The self-body conductivity is $3 \times 10^{-4}$ M$\Omega$ and 42 $\Omega$ respectively. The resistance of CVM in contact with copper electrode at 600°C and 900°C is 8.5 M$\Omega$ and 17 $\Omega$ respectively (Figure 8(f)), indicating that the contact resistance between copper electrode and CVM is remarkable in terms of self-body resistance of the material body. The contact resistance $R_i$ has significant influence on the characterization and application of electrical characteristics such as electric heating.

Conclusions

To sum up, we developed a disposable face towel derived CVM, which is prepared by a simple annealing method. Suitable carbonization temperature gives the CVM well electromagnetic shielding performance (30 dB and 8161 dB/(g/cm$^2$)), electric heating performance (can heat up exceed 60°C within 32 s under a low current of 0.25 A), strain and temperature sensing (TCR = 0.665%/°C). In addition, the CVM can be used for fire warning, where the carbonized CVM can detect the flame within 84 ms based on variation of resistance, and capable of reusability, costless and easily prepared. Therefore, this work provides a new idea and method in use of disposable face towel derived carbonized viscose mat for fabric heater, electromagnetic shielding, strain and temperature sensor, flame alarm and other technologies.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This research was supported by the Public Welfare Project of Zhejiang Province (LGF21E030005), China Postdoctoral Science Foundation (2022T150581, 2020M681917), National Natural Science Foundation of China (NSFC 51803185).

ORCID iD

Xinghua Hong https://orcid.org/0000-0002-9740-8795
References

1. Wang J, He J, Ma L, et al. Multifunctional conductive cellulose fabric with flexibility, superamphiphobicity and flame-retardancy for all-weather wearable smart electronic textiles and high-temperature warning device. Chemical Eng J 2020; 390: 124508, DOI: 10.1016/j.cej.2020.124508.

2. Hou C, Tai G, Liu Y, et al. Borophene pressure sensing for electronic skin and human-machine interface. Nano Energy 2022; 97: 107189, DOI: 10.1016/j.nanoen.2022.107189.

3. Wei X, Li H, Yue W, et al. A high-accuracy, real-time, intelligent material perception system with a machine-learning-motivated pressure-sensitive electronic skin. Matter 2022; 5: 1481–1501, DOI: 10.1016/j.matt.2022.02.016.

4. Liu D, Gao Y, Song Y, et al. Highly Sensitive Multifunctional Electronic Skin Based on Nanocellulose/MXene Composite Films with Good Electromagnetic Shielding Biocompatible Antibacterial Properties. Biomacromolecules 2022; 23: 182–195, DOI: 10.1021/acs.biomac.1c01203.

5. Chen J, Zhang J, Hu J, et al. Ultrafast-Response/Recovery Flexible Piezoresistive Sensors with DNA-Like Double Helix Yams for Epidermal Pulse Monitoring. Adv Mater 2022; 34: 2104313. DOI: 10.1002/adma.202104313.

6. Zhong M, Zhang L, Liu X, et al. Wide linear range and highly sensitive flexible pressure sensor based on multistage sensing process for health monitoring and human-machine interfaces. Chemical Eng J 2021; 412: 128649, DOI: 10.1016/j.cej.2021.128649.

7. Liu Z, Chen K, Fernando A, et al. Permeable graphited hemp fabrics-based, wearing-comfortable pressure sensors for monitoring human activities. Chemical Eng J 2021; 403: 126191, DOI: 10.1016/j.cej.2020.126191.

8. Dong J, Wang D, Peng Y, et al. Ultra-stretchable and superhydrophobic textile-based bio-electrodes for robust self-cleaning and personal health monitoring. Nano Energy 2022; 97: 107160, DOI: 10.1016/j.nanoen.2022.107160.

9. Zhang H, Chen J, Ji H, et al. Electromagnetic interference shielding with absorption-dominant performance of Ti3C2TX MXene/non-woven laminated fabrics. Textile Research J 2021; 91: 2448–2458. DOI: 10.1177/00405175211006216.

10. Faruk MO, Ahmed A, Jalil MA, et al. Functional textiles and composite based wearable thermal devices for Joule heating: progress and perspectives. Applied Materials Today 2021; 23. DOI: 10.1016/j.apmt.2021.101025.

11. Huang K, Li X, Chen W, et al. Flexible intelligent array patch based on synergy of polyurethane and nanofiber for sensitive monitor and smart treatment. Chemical Eng J 2022; 443: 136378, DOI: 10.1016/j.cej.2022.136378.

12. Raymundo-Pereira PA, Gomes NO, Machado SAS, et al. Wearable glove-embedded sensors for therapeutic drug monitoring in sweat for personalized medicine. Chemical Eng J 2022; 435: 135047, DOI: 10.1016/j.cej.2022.135047.

13. Yu M, Tao Q, Dong H, et al. Ultra-low noise graphene/copper/nylon fabric for electromagnetic interference shielding in ultra-low field magnetic resonance imaging. J Magn Reson 2020; 317: 106775. DOI: 10.1016/j.jmr.2020.106775.

14. Lin Z-I, Lou C-W, Pan Y-J, et al. Conductive fabrics made of polypropylene/multi-walled carbon nanotube coated polyester yarns: Mechanical properties and electromagnetic
interference shielding effectiveness. *Composites Sci Technology* 2017; 141: 74–82. DOI: 10.1016/j.compotech.2017.01.013.

15. Kardarian K, Busani T, Osório I, et al. Sintering of nanoscale silver coated textiles, a new approach to attain conductive fabrics for electromagnetic shielding. *Materials Chemistry Physics* 2014; 147: 815–822. DOI: 10.1016/j.matchemphys.2014.06.025.

16. Zhang D, Yin R, Zheng Y, et al. Multifunctional MXene/CNTs based flexible electronic textile with excellent strain sensing, electromagnetic interference shielding and Joule heating performances. *Chemical Eng J* 2022; 438: 135587. DOI: 10.1016/j.celj.2022.135587.

17. Sim HJ, Lee DW, Kim H, et al. Self-healing graphene oxide-based composite for electromagnetic interference shielding. *Carbon* 2019; 155: 499–505, DOI: 10.1016/j.carbon.2019.08.073.

18. Zhou W, Jiang C, Duan X, et al. Fe3O4/carbonized cellulose micro-nano hybrid for high-performance microwave absorber. *Carbohydrate Polymers* 2020; 245: 116531, DOI: 10.1016/j.carbpol.2020.116531.

19. Lou Z, Wang W, Yuan C, et al. Fabrication of Fe/C Composites as Effective Electromagnetic Wave Absorber by Carbonization of Pre-magnetized Natural Wood Fibers. *J Bioresources Bioproducts* 2019; 4: 43–50, DOI: 10.21967/jxbb.v4i1.185.

20. Chen Y, Yu Y, Zhang X, et al. High performance supercapacitors assembled with hierarchical porous carbonized wood electrode prepared through self-activation. *Industrial Crops Products* 2022; 181: 114802, DOI: 10.1016/j.indcrop.2022.114802.

21. Kumar R, Gunjal J and Chauhan S. Effect of carbonization temperature on properties of natural fiber and charcoal filled hybrid polymer composite. *Composites Part B: Eng* 2021; 217: 108846, DOI: 10.1016/j.compositesb.2021.108846.

22. Bandaru S, Murthy N, Kulkarni R, et al. Magnetic ferrite/carbonized cotton fiber composites for improving electromagnetic absorption properties at gigahertz frequencies. *J Materials Sci Technology* 2021; 86: 127–138, DOI: 10.1016/j.jmst.2021.01.041.

23. Zhu G, Jin Y and Ge M. Simple and green method for preparing copper nanoparticles supported on carbonized cotton as a heterogeneous Fenton-like catalyst. *Colloids Surfaces A: Physicochemical Eng Aspects* 2022; 647: 128978, DOI: 10.1016/j.colsurfa.2022.128978.

24. Shen X, Hu C, Ren W, et al. Optimizing magnetic/dielectric matching in permalloy/carbonized cotton fiber composites by strain-tunable ferromagnetic resonance and defect-induced dielectric polarization. *J Materials Sci Technology* 2022; 124: 174–181, DOI: 10.1016/j.jmst.2022.01.027.

25. Zhang A, Liu B, Liu S, et al. Novel approach to immobilize Au nanoclusters on micro/nanostructured carbonized natural lotus leaf as green catalyst with highly efficient catalytic activity. *Chemical Eng J* 2019; 371: 876–884, DOI: 10.1016/jcej.2019.04.149.

26. Rao L, Liu S, Wang L, et al. N-doped porous carbons from low-temperature and single-step sodium amide activation of carbonized water chestnut shell with excellent CO2 capture performance. *Chemical Eng J* 2019; 359: 428–435, DOI: 10.1016/jcej.2018.11.065.

27. Li W, Wei Z, Liu Z, et al. Qualitative identification of waste textiles based on near-infrared spectroscopy and the back propagation artificial neural network. *Textile Research J* 2021; 91: 2459–2467. DOI: 10.1177/00405175211007516.

28. Peng Y, Sun F, Xiao C, et al. Hierarchically Structured and Scalable Artificial Muscles for Smart Textiles. *ACS Appl Mater Interfaces* 2021; 13: 54386–54395. DOI: 10.1021/acsami.1c16323.
29. Rehan M, Khattab TA, Barohum A, et al. Development of Ag/AgX (X=Cl, I) nanoparticles toward antimicrobial, UV-protected and self-cleanable viscose fibers. *Carbohydr Polym* 2018; 197: 227–236. DOI: 10.1016/j.carbpol.2018.06.010.

30. Zhang X, Xia Y, Yan X, et al. Efficient suppression of flammability in flame retardant viscose fiber through incorporating with alginate fiber. *Materials Letters* 2018; 215: 106–109, DOI: 10.1016/j.matlet.2017.12.077.

31. Zhang X-S, Xia Y-Z, Shi M-W, et al. The flame retardancy of alginate/flame retardant viscose fibers investigated by vertical burning test and cone calorimeter. *Chinese Chemical Letters* 2018; 29: 489–492, DOI: 10.1016/j.cclet.2017.07.023.

32. Zhang Q, Liu D, Pei H, et al. Swelling-reconstructed chitosan-viscose nonwoven fabric for high-performance quasi-solid-state supercapacitors. *J Colloid Interface Sci* 2022; 617: 489–499, DOI: 10.1016/j.jcis.2022.03.011.

33. Kebede MA, Imae T, Sabrina, et al. Cellulose fibers functionalized by metal nanoparticles stabilized in dendrimer for formaldehyde decomposition and antimicrobial activity. *Chemical Eng J* 2017; 311: 340–347, DOI: 10.1016/j.cej.2016.11.107.

34. Scholz R, Bauer D, Hermanutz F, et al. Carbonization of special viscose fibers. *Reinforced Plastics* 2017; 61: 163–167, DOI: 10.1016/j.repl.2016.02.047.

35. Hong X, Yu R, Hou M, et al. Smart fabric strain sensor comprising reduced graphene oxide with structure-based negative piezoresistivity. *J Materials Sci* 2021; 56: 16946–16962. DOI: 10.1007/s10853-021-06365-4.

36. Cao S, Wu Z, Sun Q, et al. Gas sensing properties of cotton-based carbon fibers and ZnO/ carbon fibers regulated by changing carbonization temperatures. *Sensors Actuators B: Chemical* 2021; 337: 129818, DOI: 10.1016/j.snb.2021.129818.

37. Lu L, Xing D, Teh KS, et al. Structural effects in a composite nonwoven fabric on EMI shielding. *Materials Design* 2017; 120: 354–362, DOI: 10.1016/j.matdes.2017.02.025.

38. Zhu H, Shen F, Luo W, et al. Low temperature carbonization of cellulose nanocrystals for high performance carbon anode of sodium-ion batteries. *Nano Energy* 2017; 33: 37–44. DOI: 10.1016/j.nanoen.2017.01.021.

39. Gezahegn S, Garcia C, Lai R, et al. Benign species-tuned biomass carbonization to nano-layered graphite for EMI filtering and greener energy storage functions. *Renewable Energy* 2021; 164: 1039–1051, DOI: 10.1016/j.renene.2020.10.010.
44. Jia L-C, Nie R-P, Xu L, et al. Carbonized cotton textile with hierarchical structure for superhydrophobicity and efficient electromagnetic interference shielding. *Composites Part A: Applied Sci Manufacturing* 2021; 149: 106555, DOI: 10.1016/j.compositesa.2021.106555.

45. Zhang D, Liao Y, Bandaru S, et al. Flexible and superhydrophobic carbonized cotton fabrics for effective electromagnetic interference shielding. *J Magnetism Magnetic Materials* 2021; 540: 168434, DOI: 10.1016/j.jmmm.2021.168434.

46. Chung DDL and Ozturk M. Electromagnetic skin depth of cement paste and its thickness dependence. *J Building Eng* 2022; 52: 104393, DOI: 10.1016/j.jobe.2022.104393.

47. Hong X and Chung DDL. Carbon nanofiber mats for electromagnetic interference shielding. *Carbon* 2017; 111: 529–537, DOI: 10.1016/j.carbon.2016.10.031.

48. Chen F, Hou C, Jiang S, et al. Mechanically-compensated bending-strain measurement of multilayered paper-like electronics via surface-mounted sensor. *Composite Structures* 2021; 277: 114652, DOI: 10.1016/j.compstruct.2021.114652.

49. Shu Q, Xu Z, Liu S, et al. Magnetic flexible sensor with tension and bending discriminating detection. *Chemical Eng J* 2022; 433: 134424, DOI: 10.1016/j.cej.2021.134424.

50. Hong X, Peng T, Zhu C, et al. Electromagnetic shielding, resistance temperature-sensitive behavior, and decoupling of interfacial electricity for reduced graphene oxide paper. *J Alloys Compounds* 2021; 882: 160756. DOI: 10.1016/j.jallcom.2021.160756.

51. Yan J, Kim B and Jeong YG. Thermomechanical and electrical properties of PDMS/MWCNT composite films crosslinked by electron beam irradiation. *J Materials Sci* 2015; 50: 5599–5608. DOI: 10.1007/s10853-015-9110-1.

52. Xu Q, Si Y, He R, et al. Silk-Waste-Derived Porous Carbon for Fast Electric Heating under Safe Voltage. *ACS Appl Mater Interfaces* 2022; 14: 6005–6015. DOI: 10.1021/acsami.1c21874.