Textile & Leather Review

ISSN 2623-6281 | www.tlr-journal.com | 10.31881/TLR

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How to cite: Semanie DM, Zhang L, Wagaye BT, Zhou B, Dong Y, Guo J. Advanced Fabrication and Characterization of Hydrothermal Responsive Fabric from Microcrystalline Cellulose-Reinforced Shape Memory Polyurethane Filament. Textile & Leather Review. 2024; 7:670-687. https://doi.org/10.31881/TLR.2024.074

How to link: https://doi.org/10.31881/TLR.2024.074

Published: 8 May 2024

Advanced Fabrication and Characterization of Hydrothermal Responsive Fabric from Microcrystalline Cellulose-Reinforced Shape Memory Polyurethane Filament

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Article
https://doi.org/10.31881/TLR.2024.074
Received 2 April 2024; Accepted 30 April 2024; Published 8 May 2024

ABSTRACT
Demands for smart textiles have recently increased quickly in terms of functionality and responsiveness to wearers and environmental changes. This paper explores the development of hydrothermal responsive shape memory woven fabric from Microcrystalline Cellulose Reinforced Shape Memory Polyurethane Microcomposite Filament. The concentration of microcrystalline cellulose and drawing ratio of the filaments were first optimized according to the tensile strength and shape recovery ratio and taken as 15 wt% and 2.0 respectively. Hydrothermal responsive shape memory micro-composite filaments were then produced from shape memory polyurethane (SMPU) and microcrystalline cellulose (MCC) with optimized concentration and draw ratio by wet spinning process. The physical, mechanical, thermal and shape memory performances of the filaments were studied. The optimized filament was found to have a tensile strength of 0.91 cN/dtex and elongation of 385.2% in which the strength is much more improved when compared to a pure SMPU filament of strength 0.72 cN/dtex. The shape fixity and shape recovery results of the micro-composite filament were found to be 71.2% and 93.6% respectively. A woven fabric was manufactured from pure polyester, cotton as warp and SMPU-MCC filaments as weft and its breathability and shape memory properties were investigated. The air permeability of SMPU-PE fabrics was found to be 172.9 mm/s and 155.1 mm/s in its fixed temporary shape and recovered shape respectively. The water vapour permeability of SMPU-CT fabric was found to be 612.01 g/m^2.h and 540.28 g/m^2.h in its fixed temporary and recovered shape respectively which shows smart breathable fabrics can be made and adopted with enhanced properties.

KEYWORDS
cellulose, micro-composite filaments, hydrothermal responsive fabrics, shape memory polyurethane

INTRODUCTION

Shape memory materials (SMMs) have gained significant attention in recent years due to their ability to change their shape in response to specific stimuli (temperature, water or moisture, magnetic field, etc.), and memorize their original shape and potential applications in various fields such as smart textiles, energy harvesting, biomedical engineering and responsive materials [1]. The two most used

types of SMMs are shape-memory alloys (SMAs) and shape-memory polymers (SMPs) [2]. SMAs exhibit their shape memory effect through the transformation of austenite to martensite, a process that has found applications in textiles in various forms such as filaments or springs [3]. On the other hand, the shape memory effect of SMPs is due to the movement of hard and soft segments within polymer chains. This allows a new temporary shape to be formed and later returned to its original shape [2,4]. SMPs offer several advantages over SMAs, including greater production versatility, low manufacturing cost, high shape recovery rate, and a broad triggering temperature range. The relatively low melting point, ability to withstand up to 800% deformation, and thermoplastic properties of SMPs also enable them to be produced as thin filament yarns, composite, and various types of textile fabrics [5].

In the textile industry, SMPs can be used for temperature regulation and maintenance applications such as breathable sportswear that can provide better comfort under variable temperature and moisture environments. Since their discovery in 1980, SMPs have been developed to respond to a variety of stimuli, including heat, moisture or water, electrical current, alternating magnetic fields and light [6]. There are various types of temperature and water-responsive SMPs, but shape memory polyurethane (SMPU) is suitable for the textile application since it can be applied as coating as well as shape memory filaments used to make fabrics with a triggering or glass transition temperature (Tg) very close to a human body temperature. However, SMPU pure filaments and yarns are not strong enough to be woven or knitted into a textile fabric. Therefore, the incorporation of reinforcements mainly cellulose and carbon fibres are used in different stages of textile manufacturing processes which leads to the development of SMPU filament composites [7,8]. Korkmaz et al. produced dual moisture and temperature-responsive shape memory nanocomposite filaments from SMPU and cellulose nanowhiskers and achieved a shape recovery ratio of up to 100% with remarkable strength of filaments [9]. It has been noted that the incorporation of cellulose has improved the strength and water-responsive properties of the filaments. However, no prior studies have been conducted to produce fabrics from microcrystalline cellulose (MCC) reinforced shape memory polyurethane filaments and the effect of MCC on the breathability and overall properties of fabrics has not been investigated. The combination of MCC and SMPU provides a synergistic effect, where the MCC acts as a reinforcing agent, enhancing the mechanical strength and dimensional stability of the fabric, while the SMPU gives the shape memory effect [10].

This paper presents an advanced fabrication of woven hydrothermal responsive shape memory fabrics using a microcrystalline cellulose-reinforced shape memory polyurethane composite filament as weft and either polyester or cotton as warp yarn. The physical properties, permeability and shape memory properties of these fabrics are also examined.

EXPERIMENTAL

Materials

Pellet-type SMPU granules purchased from Sigma-Aldrich, USA were used as matrix material and Microcrystalline cellulose (MCC) (70-140µm) also purchased from Sigma-Aldrich was used as a reinforcement. In addition, N-dimethylformamide (DMF) and Polyoxyethylene sorbitan monooleate (Tween 80) both from Sigma-Aldrich were used as a polar solvent and nonionic surfactant respectively.

Production of Optimized Micro-composite Filament

A multivariate Response Surface Methodology (RSM) using central composite design (CCD) was used to determine the optimal concentration of microcrystalline cellulose (MCC) and drawing ratio. Through optimization, it was found that 15 wt% MCC (relative to the polymer mass) and a draw ratio of 2.0 were the ideal values. A spinning solution containing 25 wt% SMPU polymer, 15 wt% MCC in DMF and a non-ionic surfactant called Tween80 at a ratio of 1:2 w/w with MCC was prepared. This solution was prepared at 60 °C for 6 hours using an ultrasonic bath with a mechanical stirrer at a speed of 200 rpm [11]. The spinning solution was then extruded using Sazhuo wet spinning equipment (Shanghai Sazhuo New Material Technology CO., LTD, China) with a needle diameter of 1.05 mm with a constant flow rate of 0.81 ml/min into a coagulation bath of distilled water and then take-up speed of 1.9 m/min. The SMPU-MCC micro-composite filaments were then soaked in distilled water for 24 hours to remove any residual solvent (DMF) and dried for 10 hours at 40 °C.

Production of Hydrothermal Fabrics

Plain woven fabrics were manufactured using 250 dtex polyester and 280 dtex cotton yarns as warp yarn, while SMPU-MCC micro-composite filament in its fixed temporary shape was used as the weft. The fabrics were produced using SGA598 semi-automatic sampling loom (TONG YUAN TEXTILE MACHINERY CO.LTD, China) in which weft yarns were inserted manually using a bobbin. To make a comparison, plain-weave fabrics made entirely of 100% polyester and cotton were also produced, along with plain-weave fabric incorporating SMPU-MCC micro-composite filament. Hydrothermal responsive fabrics at their fixed temporary shape were immersed in hot water at a temperature of Tg+10 °C for ten minutes to recover to their original shape.

Determination of Tensile Properties

The mechanical properties of the filaments were assessed using the LLY-06E-500 Electronic Single Fiber Strength Tester (Laizhou Electronic Instruments Co., Ltd, China). This was done in compliance with ASTM D3822-07, using an extension rate of 200 mm/min and a gauge length of 20 mm.

Morphological Test of Filaments

TM4000 Table Top Scanning Electron Microscope (Thermo Scientific, USA) was used to assess the distribution of MCC in the filament structure and the overall morphological setup.

Determination of Functional Groups

The chemical structure and functional group of SMPU-MCC filaments were studied using Fourier Transform Infrared (FTIR) spectroscopy (PerkinElmer, USA) within a spectral range of 4000 cm^{-1} to 400 cm^{-1}.

Thermal Analyses

TGA 8000 Thermogravimetric analysis equipment (PerkinElmer Instruments, USA) was utilized to evaluate the thermal properties of micro-composite filaments. The test was conducted in a nitrogen environment, with temperatures ranging from 50 to 600 °C, and a heating rate of 10 °C/min. The decomposition temperature (T_{max}), $T_{10\%}$ and $T_{50\%}$ of the micro-composite filaments were calculated based on the thermogravimetric data.

The glass transition temperature (Tg) of filaments was examined using a Differential Scanning Calorimetry DSC 8500 (PerkinElmer Instruments, USA) according to ISO 11,357:1-7 standard. Filaments, weighing between 5 and 10 mg, were heated from -10 to 200 °C at a rate of 10 °C/min, then cooled to 20 °C at a rate of 20 °C/min and Tg was identified from the first heating.

Physical Tests

The linear density of both pure SMPU and SMPU-MCC filaments, in their original and fixed temporary shape, was measured in dtex as per the ASTM D2591-07 (Reapproved 2020) standard. The warp (EPC) and weft density (PPC) of hydrothermal responsive fabrics were determined using a thread counter. The warp or ends per centimetre (EPC) and picks or picks per centimetre (PPC) of the fabrics were determined using Pick glass (Nantong Hongda Laboratory Instrument Co., Ltd, China). The thickness of the fabrics was tested using YG (B) 141G fabric thickness tester (WENZHOU DARONG TEXTILE INSTRUMENT CO., LTD, China) according to GB/T 3820-1997 and ASTM D1777 − 96 (Reapproved 2019) with 28.7 ± 0.02 mm foot diameter and 4.14 ± 0.21 kPa applied pressure.

Shape Memory Properties of Filaments

The shape memory effect (SME) of filaments was evaluated using a mechanical-thermo-aqueous programming test. Initially, the filaments, with an initial length (Li) of 5 cm were stretched (100%) in hot water at a temperature of Tg +10 °C to a temporary length (Lt) for 10 minutes. Then, the filaments were cooled to a temperature below their glass transition (23 °C), and dried for 12 hours and a fixed

temporary length (Lf) was recorded. The shape memory effect (SME) was then triggered by reimmersing the filaments in water at a recovery temperature of Tg +10 °C for ten minutes and the samples returned to their recovered length (Lr) [5]. Finally, the shape-memory properties of the filaments were calculated using the shape-recovery ratio (Rr) and the shape-fixity ratio (Rf)(9)(12). Figure 1 shows a schematic representation of the mechanical-thermo-aqueous programming test and its parameters.

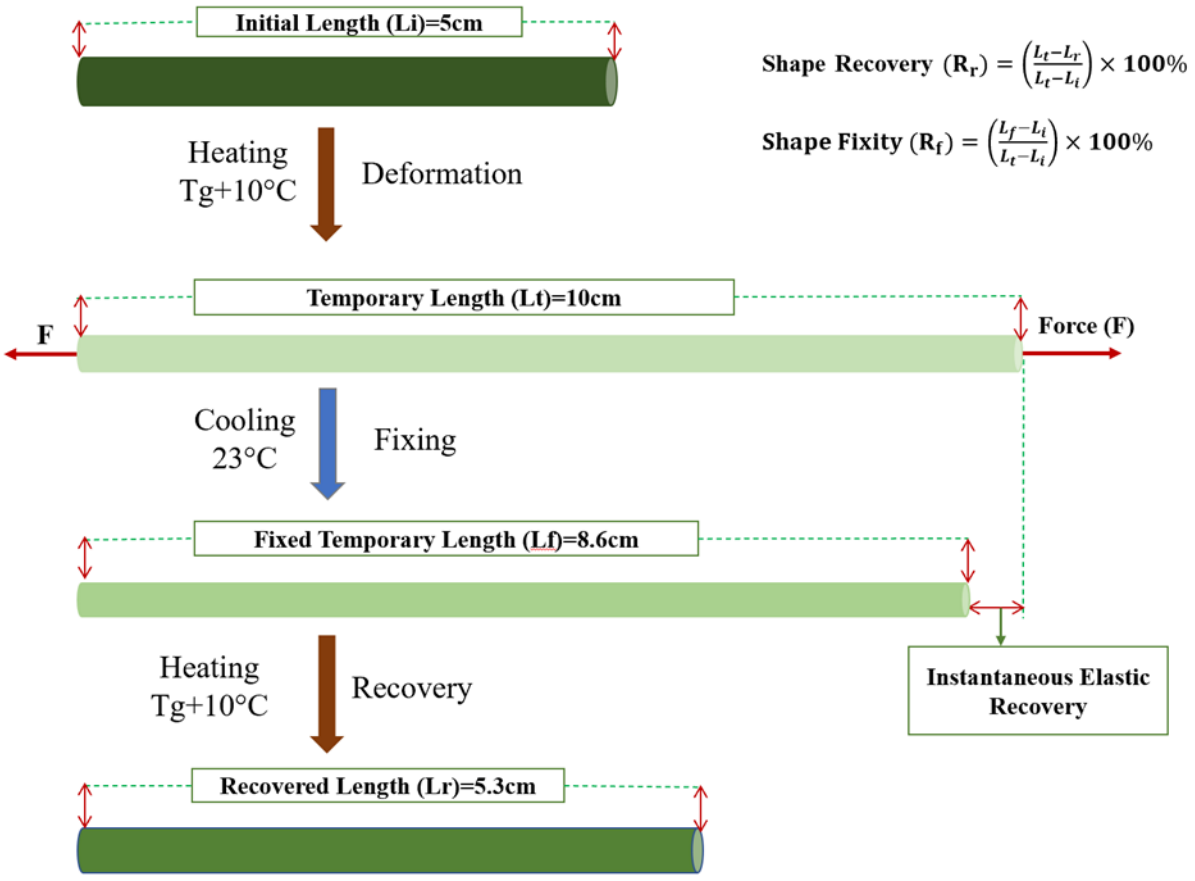

Figure 1. Schematic representation of mechanical-thermo-aqueous programming test

Air and Water Vapor Permeability Properties

The air-permeability of fabrics was evaluated in accordance with GB/T 5453-1997, using the YG641E Air-permeability Tester (WENZHOU FANGYUAN INSTRUMENT CO. LTD, China). Five samples from each fabric with a size of 20 cm^2 were used and the average permeability rate was reported as the air permeability of the fabric.

The water vapour transmission rate (WVTR) of all (pure PE, pure CT, SMPU-PE, and SMPU-CT) fabrics was measured using a YG601H computer-type fabric moisture permeability testing apparatus (Ningbo Textile Instrument, China). A separate balance with 0.0001 g weighing precision was used to measure the consecutive mass of test samples. A pair of samples each with a sample size of 28.3 cm^2 from both

pure and SMPU woven fabrics were used. A desiccant technique was used in which the specimen was sealed to the open mouth of a test cup that contained a desiccant (Calcium chloride) and put in a controlled environment. The dishes were regularly measured to establish the rate at which water vapour passes through the specimen into the desiccant. All of the experiments were carried out according to GB/T 12704.1-2009 and ASTM E96 at 38.0 °C and 90% relative humidity with an air velocity of 0.5 m/s. The water vapour transmission rate (WVTR) and Water vapour permeability (WVP) of fabrics were calculated using the formulas stated in the above standard test methods as follows:

$$\mathrm{WVTR} = \frac{\Delta \mathrm{m} - \Delta \mathrm{m}'}{\mathrm{A.t}} \quad (1)$$

$$\mathrm{WVP} = \frac{\mathrm{WVT}}{\Delta \mathrm{P}} = \frac{\mathrm{WVT}}{\mathrm{Pcb(R1-R2)}} \quad (2)$$

$$\text{Water Permeability} = \mathrm{WVP} \times \text{Thickness} \quad (3)$$

Where WVTR is the water vapour transmission rate of fabrics in g/m^2.h, Δm is the difference between two weightings of the same test combination in g, Δm' is the difference between two weightings of the blank sample in g, A is the effective test area in m^2 (0.00283 m^2 was used), t is test time in h, WVP is water vapour permeance of fabrics in g/m^2.Pa.h. ΔP is the difference in water vapour pressure on both sides of the sample in pa, Pcb is saturated water vapour pressure at test temperature in pa (6625.056 Pa at 38.0 °C), R1 is the relative humidity of the test chamber during the test (90%) and R2 is relative humidity in the cup (0%).

RESULTS AND DISCUSSION

Mechanical Properties of Filaments

The strength of shape-memory polyurethane fibres can be improved by the incorporation of reinforcing materials such as cellulose [3,10,11,13]. Figure 2 shows the stress-strain curves of pure SMPU and SMPU-MCC micro-composite filaments at their original and fixed temporary shapes. In its original shape, the SMPU-MCC micro-composite filament has 0.91 cN/dtex tenacity and 385.2% elongation. However, these values decreased to a tenacity of 0.74 cN/dtex and an elongation of 331.8% in its fixed temporary shape. Pure SMPU filaments have a tenacity of 0.72 cN/dtex and an elongation percentage of 519.3% in their original shape and 386.4% in their fixed temporary shape. SMPU-MCC micro-composite filaments have higher strength due to better load transfer due to matrix-cellulose chain alignment [11].

Table 1. Tensile properties of micro-composite filaments at their original and fixed temporary shape

	Original shape (OS)		Fixed temporary shape (FTS)	
Filament code	Tenacity (cN/dtex)	Strain (%)	Tenacity (cN/dtex)	Strain (%)
SMPU	0.72	519.3	0.61	386.4
SMPU-MCC	0.91	385.2	0.74	331.8

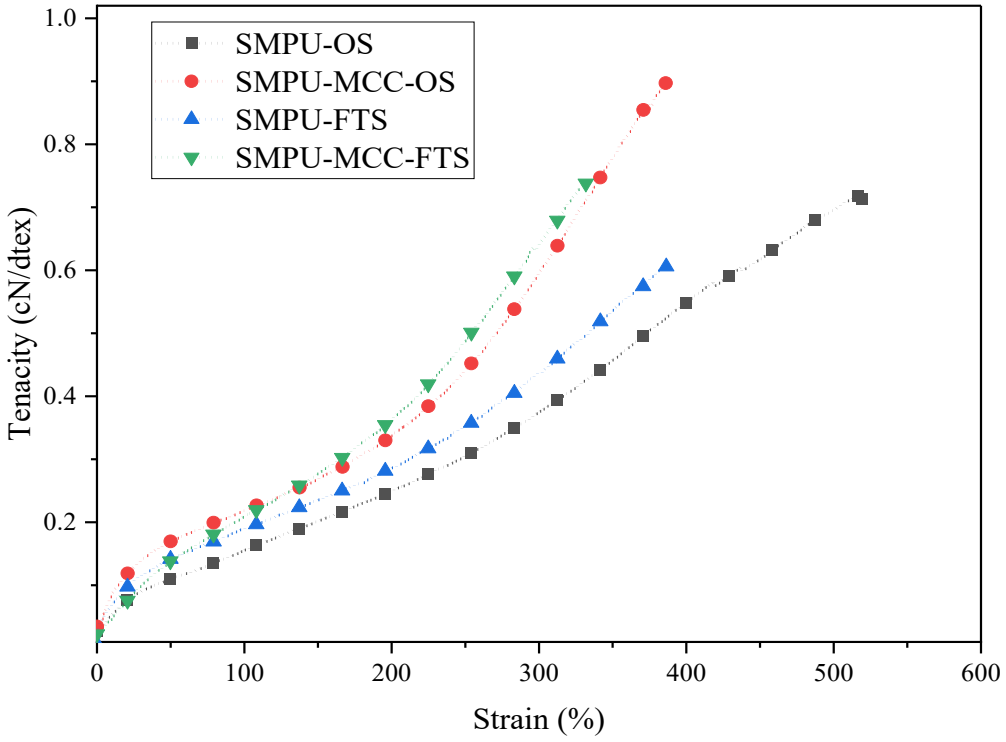

Figure 2. Tensile properties of Microcomposite filaments at their original and fixed temporary shape

Morphological Analyses

Figures 3 a & b for pure SMPU filaments and c & d for SMPU-MCC micro-composite filaments show the longitudinal and cross-sectional views of the two types of filaments. The figure shows that the cross-section of pure SMPU is slightly irregular and has foldings, microcracks and a distinct fibre edge [14]. This was explained by Korkmaz et al. as the lack of reinforcement materials such as cellulose, which affects viscosity and causes a low mass transfer rate difference between the coagulating solvent diffusion into the spinning solution and the solvent extraction into the coagulation bath [11]. Hence, the cross-sections of SMPU-MCC micro-composite filaments are comparatively regular and circular [15-17].

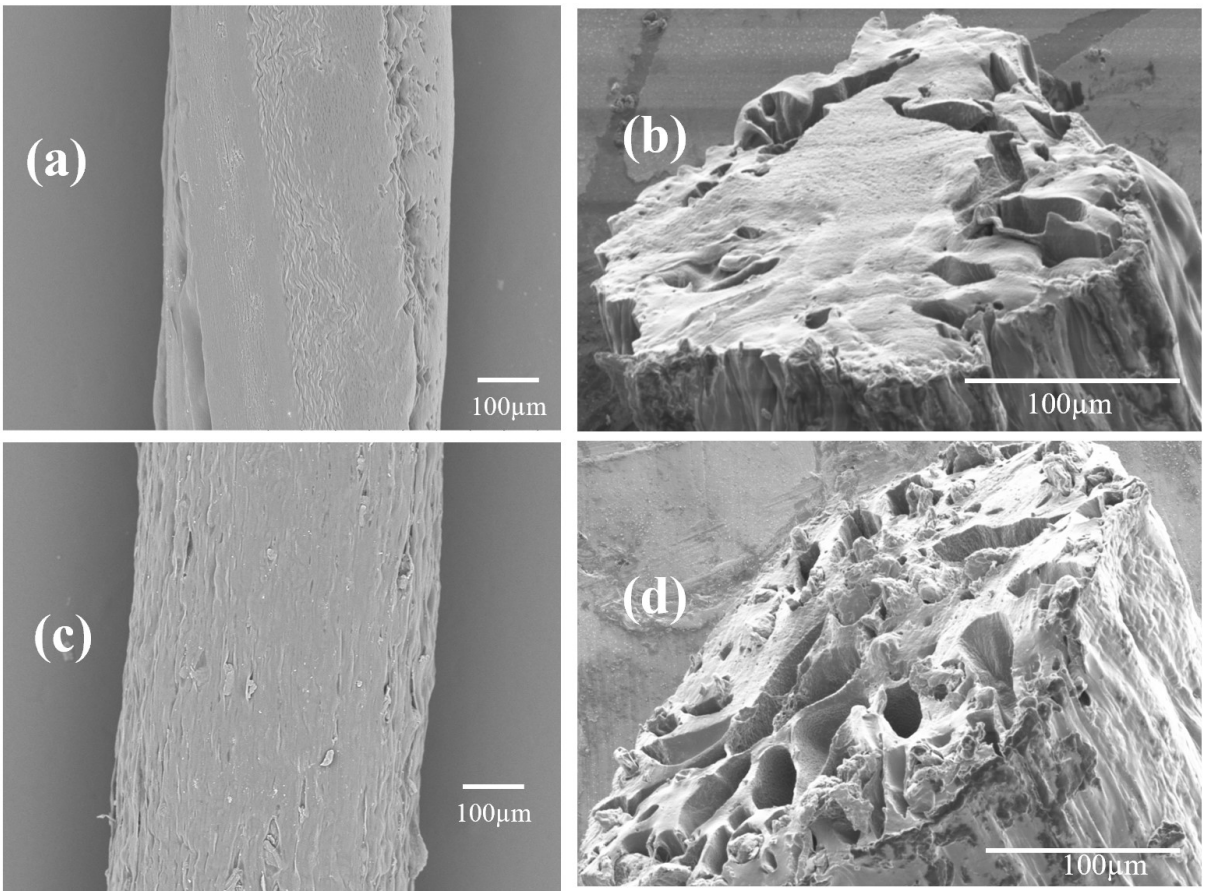

Figure 3. Longitudinal (on the left) and Cross-sectional (on the right) SEM images of a) and b) pure SMPU-2.0; c) and d) SMPU-MCC

Determination of Functional Groups

The FT-IR spectra of SMPU-MCC and pure SMPU filaments are shown in Figure 4. A peak at 3271 cm^{-1} corresponds to the stretching vibrations of the (-OH-) and (-NH-) groups in SMPU polymers. The peaks 2850 cm^{-1} show the symmetric stretching of (-CH-) and 1627 cm^{-1} shows the bending vibrations of (-C=O-) groups of SMPU. The particular peaks correspond to the stretching vibrations of the(-NH-) and (-OH-) shift for SMPU-MCC filaments from 3271 cm^{-1} to 3346 cm^{-1}. This shift shows the presence of extra hydroxyl (-OH) groups from microcrystalline cellulose [15,18,19]. For SMPU-MCC, the distinctive peaks at 2949 cm^{-1} show the (-CH2-) and (-C-H-) stretching vibrations of the hydrocarbon chains. The peak at 1728 cm^{-1} corresponds to the (-C=C-) bending vibration of alkenes found in SMPU and cellulose, whereas the peak absorption at 1627 cm^{-1} and 1540 cm^{-1} shows (-C=O-) stretching vibrations [14,16,20,21].

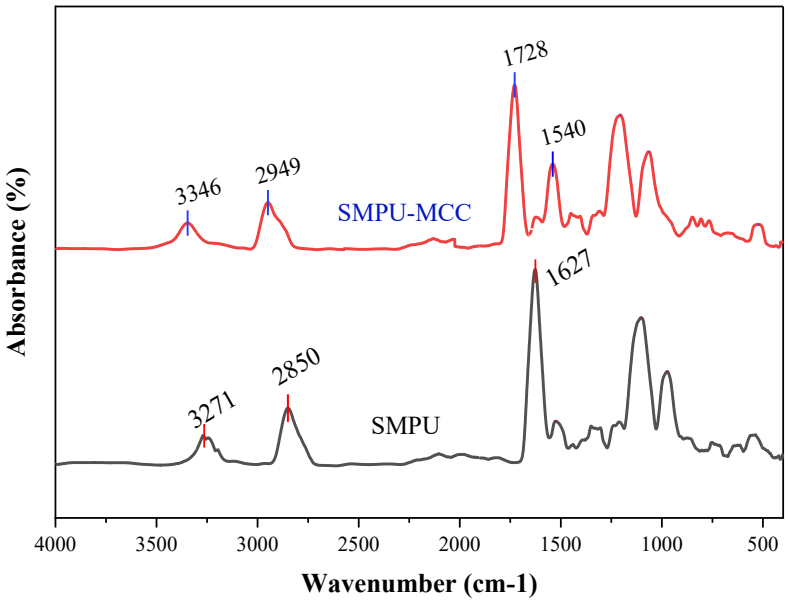

Figure 4. FTIR spectra values of pure SMPU and SMPU-MCC micro-composite filaments

Thermal Analyses

Thermogravimetric Analysis (TGA) test results of SMPU-MCC micro-composite filaments and pure SMPU filaments are shown in Figure 5. The TGA curve showed that the $T_{10\%}$ temperature rose from 309.9 °C for pure SMPU filaments to 325.6 °C SMPU-MCC microcomposite filaments and the $T_{50\%}$ temperature increased from 336.9 °C to 380.96 °C for SMPU-MCC microcomposite filaments compared to pure SMPU. This indicates that the presence of MCC improved the thermal stability of filaments. The degradation temperatures at $T_{10\%}$ can be attributed to the removal of loosely bound volatile compounds whereas the first step degradations at around 343 °C is the most representative indicator of the decomposition of SMPU polymer hard segment linkages [11]. The DTG graph shows a significant increase in the maximum decomposition temperature (T_{max}) of the filaments from 370 °C (SMPU) to 390 °C (SMPU-MCC), indicating better thermal stability due to interaction between the SMPU matrix and MCC through hydrogen bonding [22]. Gan et al. indicated that strong intermolecular bonding increases the energy needed for macromolecule chain breaking, which improves thermal stability [8,23]. In addition, the char residue for pure SMPU and SMPU-MCC micro-composite filaments were found to be 4.96 wt% and 10.97 wt% respectively.

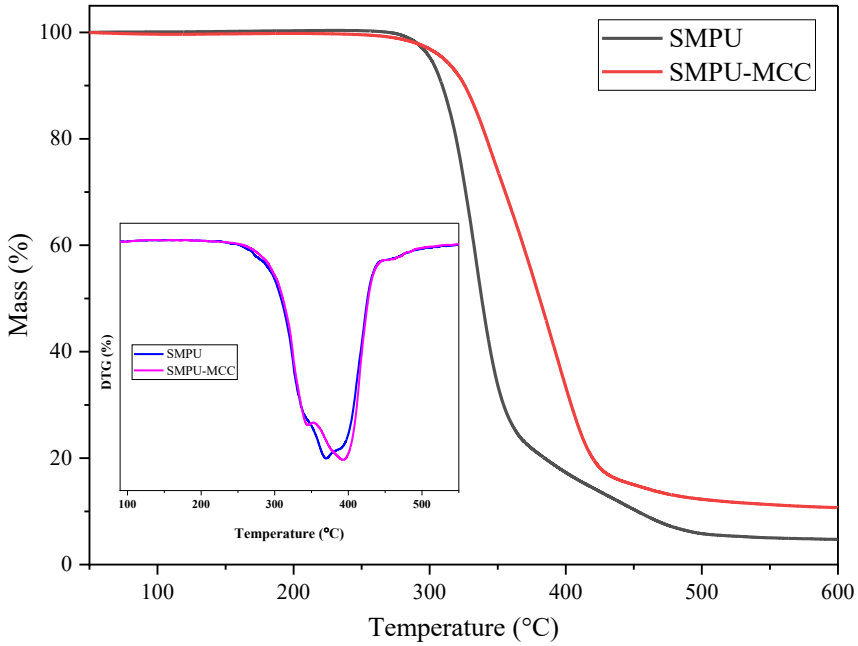

Figure 5. TGA and DTG curves of SMPU and MCC-SMPU micro-composite filaments

As indicated in Figure 6 and Table 2, the DSC test results showed that the Tg of the pure SMPU filament and SMPU-MCC micro-composite filaments were 41.65 °C and 41.02 °C respectively. The presence of MCC in the SMPU filament structure resulted in slightly lower Tg and higher heat absorption than pure SMPU micro-composite filaments [24]. This is consistent with Korkmaz et al. and Gan et al. where a reduction in Tg of composite fibres after the incorporation of cellulose was reported [8,11]. Korkmaz et al. studied that the plasticizing effect and micro-Brownian thermal movements of molecular chain segments caused by CNW particles contribute to a reduction in Tg [11].

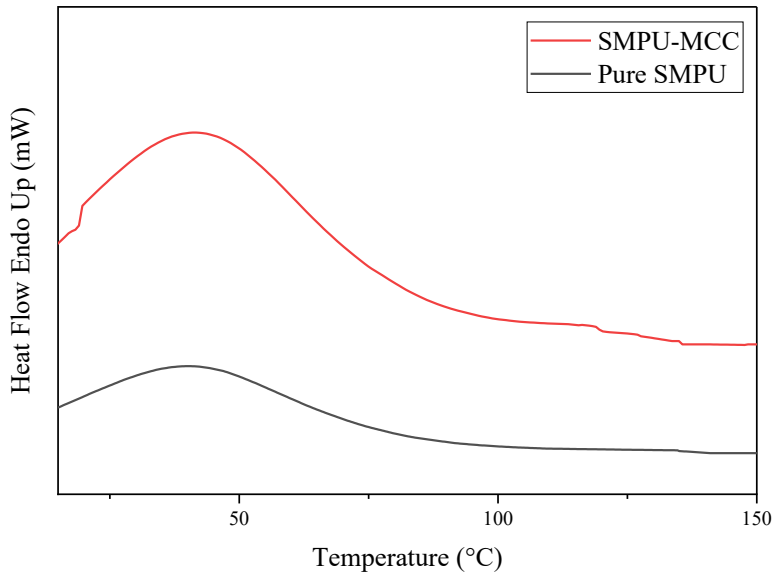

Figure 6. First heating DSC curves for pure SMPU and SMPU-MCC microcomposite filaments

Table 1. First heating DSC results for pure SMPU and SMPU-MCC micro-composite filaments

Sample Code	Tg (°C)
SMPU	41.65
SMPU-MCC	41.02

Shape Memory Properties

The shape memory characteristics of micro-composite filaments and pure SMPU at a triggering temperature of Tg+10 °C are shown in Figure 7. The micro-composite filament (SMPU-MCC) has a shape fixity ratio of 71.3%, which is higher than that of pure SMPU filaments (64%) and suggests that the SMPU-MCCC filaments will be able to retain its fixed temporary shape when the load is removed [14]. However, the shape recovery ratio decreases when Microcrystalline Cellulose (MCC) is added to the SMPU filaments. This is due to the reduced mobility of the soft segments as the addition of MCC increases the strength and rigidity, which is associated with an increased hard segment portion of the filaments [14]. For MCC-SMPU, the shape recovery ratio was found to be 93.6%, while the shape recovery of pure SMPU filaments was 96%. These values align with Korkmaz et al., which reported a shape recovery ratio between 91% and 100% for SMPU reinforced with cellulose nanowhiskers [11]. The moisture-responsive shape memory effect of MCC-SMPU filaments is primarily due to the incorporation of MCC, which introduces hydrophilic properties to the shape memory polyurethanes. Hydrogen bonds will be formed between water molecules and the hydroxyl groups in MCC when the filaments are exposed to hot water above Tg [11].

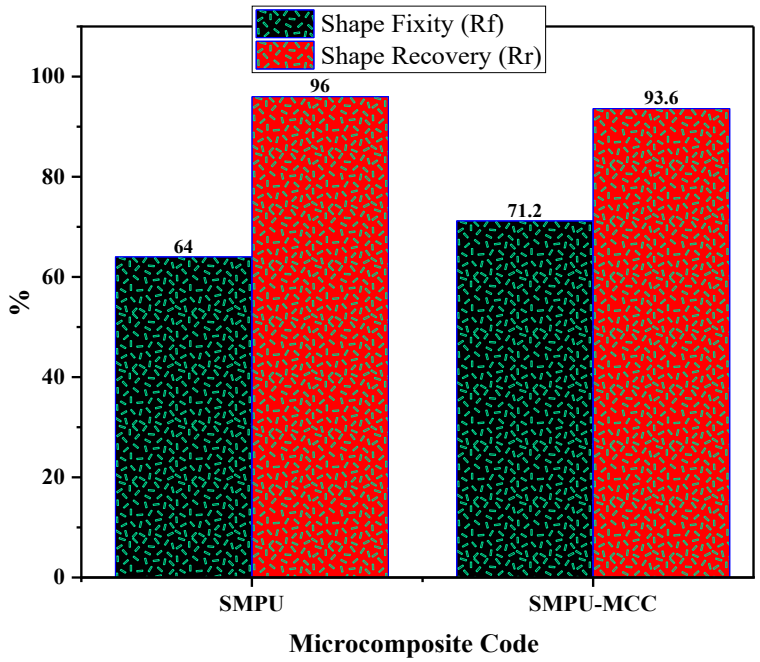

Figure 7. Shape memory properties of pure SMPU and SMPU-MCC filaments

Physical Property of Filaments

Figure 8 shows the linear densities of SMPU-MCC micro-composite filaments and pure SMPU in their original shape (OS) and fixed temporary shapes (FTS), ranging from 155.3 to 182 dtex. Incorporating MCC into the SMPU matrix influences the linear density of the microcomposite filaments. Pure SMPU filaments have a linear density of 176.6 dtex, whereas SMPU-MCC filaments exhibit a higher linear density value of 181.4 dtex. This increase in linear density indicates that the stiffness and density of MCC contribute to the overall mass of the composite filament [2,11]. The linear density of both filaments in their fixed temporary shape is smaller compared to their original shape. This reduction in linear density is related to the stretching of the shape memory filaments, which leads to a decrease in the mass per unit length.

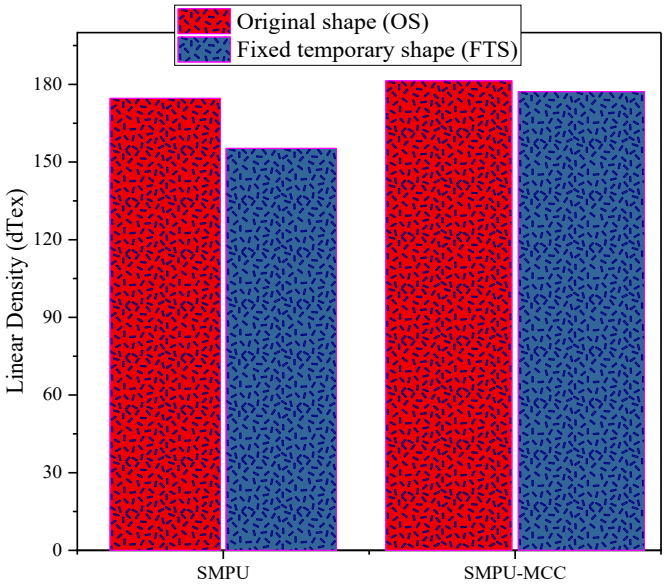

Figure 8. Linear density of filaments at their a) original shape b) Fixed temporary shape

Physical Property of Fabrics

Table 3 shows the warp density and thickness values for pure fabrics with SMPU micro-composite filaments in both recovered shape (RS) and fixed temporary shape (FTS). The thermodynamics of hydrothermal shape memory woven fabric is based on the variation in pore size between yarns in the fabric. The fabric had an open structure in fixed temporary shape (FTS), but a more closed structure in recovered shape (RS), due to dynamic changes in the diameter of shape memory filaments. These diameter changes affect the fabric density and thickness [3]. As a result, the warp density and thickness of the fabrics in the fixed temporary shape for both SMPU-polyester (PE) and SMPU-cotton (CT) fabrics are greater than that of pure polyester and cotton fabrics. This increase is related to the recovery of the weft SMPU filaments to their original shape after the shape memory effect was triggered by

treating the fabrics in hot water at Tg+10 °C. These results are consistent with the results reported by Bertran et al., where polyester yarns are used as the warp yarn and pure SMPU filaments as the weft yarn in different weft ratios and found that the fabric parameters including tightness and thickness increase after the load was removed from weft yarns [3].

Table 2. Physical properties of different fabrics

Fabric	Ends per cm (EPC)		Picks per cm (PPC)		Thickness (mm)	
Pure PE	18		46.2		0.60	
Pure CT	17.6		42.6		0.69	
	FTS	RS	FTS	RS	FTS	RS
SMPU-PE	17.8	22	56	56.4	0.77	0.80
SMPU-CT	18.2	21.2	59	58.6	0.78	0.79

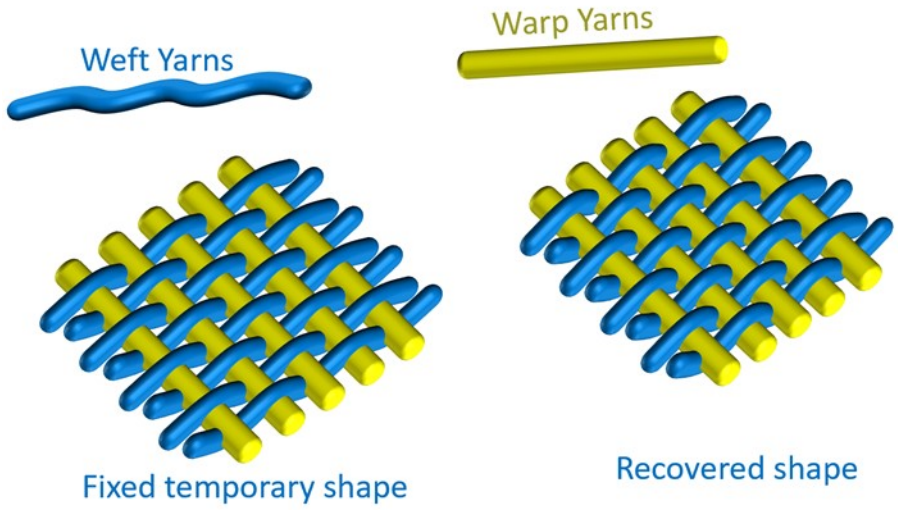

Figure 9. A simplified representation of the hydrothermal plain-weave fabric with weft SMPU-MCC filament

Air and Water Vapor Permeability Properties

Air and water vapour permeability tests were carried out to assess the breathability and shape memory properties of hydrothermal responsive fabrics. Results from pure polyester (PE) and pure cotton fabrics were used as references. As shown in Table 4, the air permeability of shape Memory Polyurethane-Cotton (SMPU-CT) fabric in its fixed temporary shape (FTS) (213.2 mm/s) is higher than that of its recovered shape (RS) (187.4 mm/s). Additionally, the air permeability of pure PE fabric (214.9 mm/s) is higher than that of SMPU-PE fabrics in both shapes and the air permeability of pure cotton fabric is also higher than SMPU-CT fabric in both shapes due to the difference in fabric density. Despite having a slightly lower air permeability due to its high thread density, hydrothermal responsive fabrics still exhibit comparable air permeability to pure cotton and polyester fabrics. This indicates that the use of

shape-memory polyurethane micro-composite filaments as the weft can provide similar air circulation and comfort as cotton and polyester fabrics, while also providing shape-memory properties for body moisture and temperature regulation. Air permeability, which shows how porous the fabrics are, affects both heat and sweat flow within the fabric and is affected by filament structure and properties. This can be observed in SMPU-PE hydrothermal responsive fabrics, where the air permeability at their fixed temporary shape (172.9 mm/s) is higher than their recovered shape (155.1 mm/s). SMPU-MCC filaments enable the fabric to change its air permeability by adjusting the porosity. This helps the wearer be comfortable in various body or environmental conditions [3,10].

Table 4. Air permeability properties of fabrics

Fabric	Air permeability (mm/s)	
Pure PE	214.9	
Pure CT	221.2	
	Fixed temporary shape (FTS)	Recovered shape (RS)
SMPU-PE	172.9	155.1
SMPU-CT	213.2	187.4

Figure 10 shows the water vapour transmission rate (WVTR) and water permeability (WP) of pure and hydrothermal responsive fabrics. The WVTR of SMPU-PE and SMPU-CT hydrothermal responsive fabrics is 541.7 g/m^2.h and 612.01 g/m^2.h respectively in their fixed temporary shape, and 505.65 g/m^2.h and 540.28 g/m^2.h respectively in their recovered shape. The WVTR of pure polyester fabrics is lower than that of SMPU-PE fabrics in their fixed temporary shapes. This can be attributed to the smooth fibre structure, crystallinity, hydrophobicity and the lack of -OH- groups in polyester morphology which affects the movement or passage of water molecules through it. In addition, SMPU-PE hydrothermal responsive fabrics exhibit a higher WP than pure polyester fabrics, even at higher fabric density (as stated in Table 3). This is due to the incorporation of microcrystalline cellulose, which improves the interaction and absorption of fabric with water and facilitates the movement of water molecules through the fabric by creating hydrogen bonds with water molecules. This is consistent with the findings of Jahid et al. and Korkmaz et al. where the water vapour transmission largely depends on the water affinity of the functional group of polymers [10,25]. The WVTR of pure cotton fabrics (657.24 g/m^2.h) is higher than hydrothermal responsive fabrics made from microcrystalline cellulose incorporated shape memory polyurethane at both fixed temporary and recovered shapes. This is due to the low water affinity and reaction property of polyurethane molecules compared to cellulose. Pure cotton fabrics can create more hydrogen bonds with water than SMPU-CT fabrics. Both hydrothermal responsive shape memory fabrics in their fixed temporary shape have higher WVTR than fabrics in their recovered shape, facilitating the passage of water vapour in and out of the body related to the

temperature and humidity of the environment. This can be attributed to the change in the pore size of the fabrics, which occurs when shape memory filaments recover to their original shape. This is consistent with the findings of Bertran et al. where fabric breathability increases with the incorporation of more shape-memory polyurethane [3].

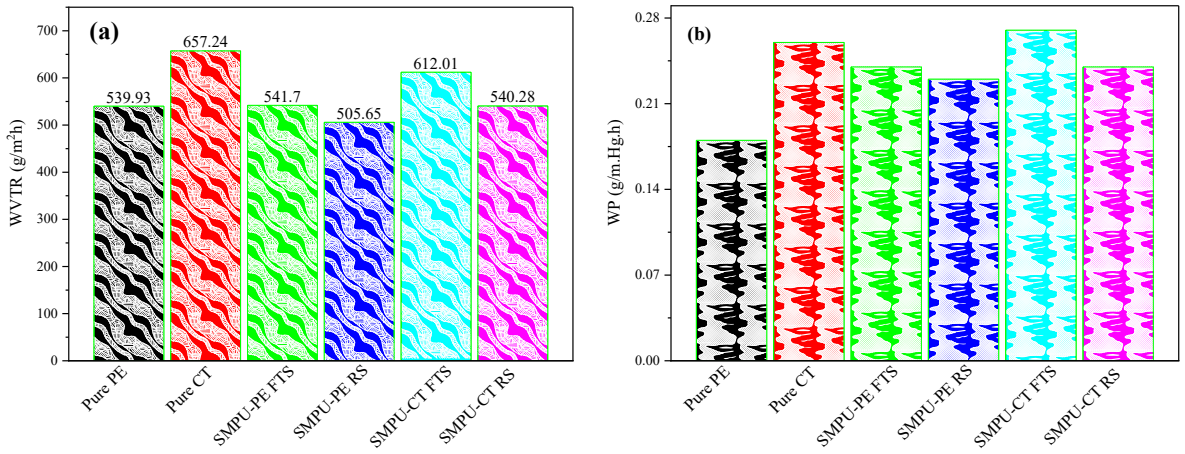

Figure 10. Water vapour transmission rate (WVTR) (a) and water permeability (WP) (b) of fabrics

CONCLUSION

This study investigated the production and characterization of plain woven, shape memory fabrics with responsive properties to moisture and heat. The fabrics were constructed using shape memory micro-composite filaments as weft yarns, woven with either polyester or cotton warp yarns. The presence of microcrystalline cellulose in the composite filament increased the mechanical, crystallinity and water-responsive shape memory properties of the filaments. The shape fixity and recovery of pure SMPU and SMPU-MCC filaments were evaluated by using a mechanical-thermo-aqueous programming test in hot water at a temperature of Tg +10 °C and exhibited a shape recovery of 93.6%. The air permeability of hydrothermal responsive fabrics was 172.9 mm/s and 213.2 mm/s for SMPU-PE and SMPU-CT at their fixed temporary shape and 155.1 mm/s and 187.4 mm/s at their recovered shape respectively. In addition, the water vapour transmission rate of hydrothermal responsive fabrics is 541.7 g/m^2.h and 612.01 g/m^2.h for SMPU-PE and SMPU-CT at their fixed temporary shape and 505.65 g/m^2.h and 540.28 g/m^2.h at their recovered shape respectively. These results show that hydrothermal responsive fabrics can offer better breathability and maintain body thermodynamics indicating a potential application in smart textiles such as sportswear, waterproof and breathable clothes, socks etc.

Author Contributions

Conceptualization – Semanie DM; methodology – Semanie DM; formal analysis – Semanie DM; investigation – Semanie DM; writing-original draft preparation – Semanie DM; writing-review and editing – Zhang L, Wagaye BT, Zhou B; visualization – Dong YL; supervision – Guo JS. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Funding

This research received no external funding.

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