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RESEARCH ON SHAPE MEMORY PROPERTIES OF WOOL YARN AND WOOL KNITTED FABRIC AFTER DESCALING TREATMENT BY ULTRASONIC

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ABSTRACT

Wool is one of the most widely used proteinic material for textile products due to its outstanding desirable properties including excellent thermal insulation, breathability, flame retardancy and comfort properties. Moreover, wool has shape memory capability, so it is good candidate for thermo-regulating clothes. However, wool fibers have a surface structure of overlapping cuticle cells known as scales which significantly affect fiber properties. This paper investigated the appearance, strength, extension and the shape memory behavior of the wool yarn and also the wool rib knitted fabric before and after descaling its cuticle cells using calcium carbonate nano powder (CCNP) powder with the concentration of 2 g/l, 5 g/l, and 10g/l in ultrasonic bath. The shape memory behavior of wool yarn, and rib knitted fabric were examined by changing between the warm-humid (temperature of 28°C; humidity of 90%) and the cold-dry condition (temperature of 8oC; humidity of 20%). The results showed that the increase of CCNP concentration improved the descaling effect, which resulted in less sharp morphology of scales on the wool fiber surface. Wool yarn breaking strength and elongation tended to increase due to the increase of CCNP concentration, while the value of CV (%) decreased. Moreover, the results demonstrated that the length of wool yarn did not change much for both original and treated yarns while descaled fabric possessed higher shape memory ability than untreated fabric, especially in vertical direction with 100 % of the original value, and the horizontal shape memory ability was in range of 93.8 % to 97.6 %.

KEYWORDS

Calcium Carbonate Nano Powder, Knitted Fabric, Shape Memory Ability, Ultrasonic, Wool Fibre.

INTRODUCTION

knitted fabric thermal comfort properties. For more detail, the results showed plain knitted fabric with loose structure and the fabric knitted with single-ply yarn possessed the lowest thermal resistance value and the highest relative water vapor and air permeability value. A. Majumdar [4] investigated the thermal properties of different knitted fabric structures made of blend fibers (100% cotton, 50:50 cotton: bamboo and 100% bamboo) to manufacture three types of knitted structures that were plain, rib and interlock. The paper demonstrated that thermal conductivity of knitted fabrics depending on the material ratio and knitted structure. This value reduced as the proportion of bamboo fiber increases. And the thermal conductivity and thermal resistance values of interlock fabric was the maximum followed by the rib and plain fabrics. Moreover, the water vapor permeability and air permeability of knitted fabrics increases while the bamboo fiber ratio increased.

Shape memory polymers are considered as stimuli-responsive materials which possessed double-shape possibility [5]. This kind of polymer could be returned to desired permanent shape from their shape in a predefined way from temporary shape if they exposed to an appropriate stimulus such as temperature. Application in textile field of shape memory polymer was carried out for recent years [4,6-9] to improve the function of textile products. Shape memory polymer fabrics can flexibly respond to environmental stimuli, make corresponding changes in morphological/fabric structure, presenting outstanding advantages and bringing garment an intelligent thermal-moisture management [6-7]. Judit Gonzalez Bertran et al. had studied shape memory polymers in the form of filament yarns integrated in the fabrics [8]. In the research, the shape memory polyurethanes (SMPUs) woven with reversible thermodynamic properties produced using weft SMPU filament yarns interlaced into polyester (PES) fabrics. The different ratios of weft SMPU filament yarns (PES/SMPU 1:0; 3:1; 1:1; 1: 3, and 0:1) were investigated. Then the fabric thermodynamic properties such as thermal resistance, permeability index, shape memory effect, and mechanical performance were examined and

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compared to the 100% PES reference fabric. The results showed that SMPU-based fabrics developed were classified as highly breathable with water vapor resistance < 6 m^2Pa/W and thermally comfortable (water vapor permeability index < 0.3). The fabrics with weft SMPU filament yarns had temperature stimuli at Tg, while there was not thermodynamic behavior for 100% PES woven fabric. According to the authors the reason was the improvement in thermal protection against increase of ambient temperature, while still maintain good moisture management properties for the ratio PES/SMPU 0:1. Among many shape memory polymers applied on textile industrials, the thermal and hygrothermal capability of wool materials make this kind of textile material considered as natural shape memory polymers. Jinlian Hu et all. [5] have reviewed the fundamental concept of the shape memory polymers and the fundamental aspects of the shape-memory effect to discuss the shape memory behavior of wool materials. Moreover, the authors have investigated the effects of synthetic shape memory polymers on the thermal and hygrothermal of the woven wool fabrics to show the shape memory behavior of treated wool. According to Crawshaw [10], the shape memory behavior of wool materials may be explained by their structure. As known, wool fiber is surrounded by cuticle cells which overlap in one direction and which consist at least of four layers, the epicuticle, the A-layer and the B-layer of the exocuticle, and the endocuticle. The cuticle surrounds a compacted mass of cortical cells of spindle form aligned with the fiber axis and with their fringed ends inter digitating with each other. Both cuticle and cortical cells are separated by the cell membrane complex comprising internal lipids and proteins. This cell membrane complex is the component between the cells that guarantees strong intercellular bonding via proteins generally called desmosomes. The cross-sections of the cortex cells showed the presence of macrofibrils oriented in the direction of the fiber axis and embedded into the intermacrofibrillar matrix which contains cytoplasmic residues and nuclear remnants [10-11]. The scale, which is a big obstacle for wool in a wide range application in textile, can be removed easily by chlorinated chemicals, but it is toxic for users and environment. Some recent researches have investigated new and clean method for wool treatment to reduce the scale and to obtain the suitable characteristic for destinated application [12-15]. Salwa Mowa and Rania El-Newash [12] had improved garment appearance and performance wool fabric by using bio-treatment (two commercial proteases) and chemical wool treatments by softener based on poly amino siloxane (PAS). The authors had studied the physical and mechanical properties of treated wool fabric as descaled surface of bio-treated wool. The research reported that the improve in drapability, drape coefficient, smoothness, yellowness index, and electrical conductivity of the treated wool fabrics. Honglian Cong et al. have studied the influence of the treatment with oxygen low-temperature plasma on the knitted woolen fabrics for sportswear [13]. Nine groups knitted fabric with different technical characteristics were investigated by the changes in the surface morphology and chemical composition of wool fibers before and after plasma treatment. The paper has demonstrated that the anti-felting, bursting strength and moisture absorption of the knitted woolen fabrics were improved. The reason was explicated by scales in the wool fiber surface were seriously etched after oxygen low-temperature plasma treatment. Meanwhile, the fabric showed less time to dry. Wool descaled method using calcium carbonate particles was investigated [14, 15]. Ghasemi et al. [14] studied a descale method using calcium carbonate Nano particles (CCNP) with diameter of 60 nm based on abrasion effect in an ultrasonic bath. In the research woolen samples (fiber and yarn) were sonicated with different concentration (2, 6 and 10g/l) of CCNP. Tensile properties of the yarns, directional friction effect of the fibers and SEM images of the fibers were examined. The authors reported that sonicated CCNP treatment of wool yarn reduced its tenacity, extension and work of rupture and increased its coefficient of friction. The reason was the descaling of wool samples in comparison to the raw wool. The authors also explained that abrasion of thin layer from surface of the fibers changing the sharpness of the scales. The results showed that, scales were observed clearly changing at the CCNP concentration of 6 g/l and they were nearly removed at the concentration of 10g/l. Jinlian Hu et al. [9] reported the advantage of descaled wool yarn in thermo-regulating textile application due to the change in pore size of knitted fabric. The research showed that knitted descaled woolen fabric had actually water-responsive pore ability due to changing stitch shape and can be considered as a seasonal garment material with body sweat acting as a stimulator for thermoregulation. According to the authors, descaled wool knitted fabric can provide a cooling sensation during sweating due to the water-responsive switching (opening/closing) of the knit stitches. The results also demonstrated fabric pore area increased by more than 70% at 100% water absorption, and the air permeability of the knitted descaled woolen fabric increased significantly to 60% with increasing water absorption. However, the detail of wool fiber descaling process was not mentioned.The aim of this research was examination of shape memory characteristics of wool yarn and the wool knitted fabric descaled by the abrasion effect of CCNP in combination with ultrasonic energy.

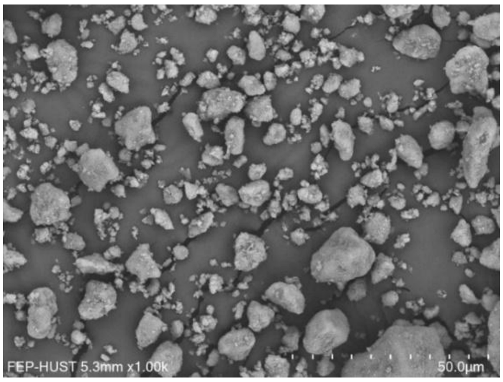

Figure 1: SEM image of calcium carbonate nano powder used to descale wool yarn.

MATERIAL AND METHODS

Materials

Original wool yarn Ne 40/1 without descaling was supplied by Xinao Company (China). Calcium carbonate nano powder (CaCO3 nano powder) (CCNP) with particle size in range of 500 nm ÷ 50 nm, which was used for abrasion in descaling process, was presented by Vietchem Company (Vietnam).

Methods

Shape memory characteristics of wool yarn

Original wool yarn was descaled by $CaCO_3$ nano powder, using an ultrasonic bath of Mujigae at 40°C and 40 Hz for 20 minutes. $CaCO_3$ nano powder was dispersed in distilled water at different concentrations of 2, 5 and 10 (g/l). After the descaling process, the yarn sample was rinsed carefully with distilled water to eliminate the residual powder and then was dried at 45 °C for 1 hour. The morphology of scales on wool yarn surface before and after descaling treatment was observed by a scanning electron microscope of JEOL at the voltage of 5kV. The change in the sharpness of the wool fiber scales was defined by angle formed from two tangent lines to the two sides of the scale. The breaking strength and elongation of wool yarn before and after descaling treatment was determined according to ISO 2062:2009 testing standard. The shape memory behavior of wool yarn was evaluated according to the change in yarn length by altering environment temperature and humidity. For all yarn samples (original yarn and yarn descaled with 2 g/l, 5 g/l and 10 g/l of $CaCO_3$ nano powder), an original length L_o of 50 (mm) was marked on the yarn that was storage at cold-dry chamber (temperature of 8°C; humidity of 20%) for 24 hours. After that, the yarns were moved into a warm-humid chamber (temperature of 28°C; humidity of 90%) for 30 minutes and then the temporary length L_t was measured. The elongation of yarn E [%] was determined by equation (1):

$$E\ [\%] = \frac{L_t - L_o}{L_o} \times 100 \quad (1)$$

From the warm-humid chamber, the yarn was moved back to the cold-dry chamber (temperature of 8 °C; humidity of 20%) and after 30 minutes of storage there, the memorable length L_m was determined. The shrinkage of yarn S (%) was determined by equation (2):

$$S\ [\%] = \frac{L_t - L_m}{L_t} \times 100 \quad (2)$$

And the shape memory ability of yarn M (%) was calculated by the equation (3):

$$M\ [\%] = \frac{L_m}{L_o} \times 100 \quad (3)$$

Shape memory characteristics of wool knitted fabric

To evaluate the shape memory behavior of wool yarn fabric, rib 1:1 knitted fabric was made from original wool yarn (plied by 4) on a flat knitting machine of Singer (knitting gauge G7). The rib knitted fabric was then treated by descaling process at different concentration of $CaCO_3$ nano powder (2 g/l, 5 g/l and 10 g/l), similarly to the wool yarns treatment.

Shape memory behavior of rib knitted fabric was expressed by the change in wale spacing (for horizontal direction) and course spacing (for vertical direction) measured by ASTM D3887, when the environment switched between cold-dry (temperature of 8°C; humidity of 20 %) and warm-humid (temperature of 28°C; humidity of 90%) condition, as was conducted for wool yarns in the section 2.2.1. The measurement of all samples were taken immediately after the changing cold- warm-humid condition. The horizontal elongation E_h [%], horizontal shrinkage S_h [%] and horizontal shape memory ability M_h [%] were deduced from original wale spacing W_o, temporary wale spacing W_t and memorable wale spacing W_m by equation (4)-(6) below:

$$E_h\ [\%] = \frac{W_t - W_o}{W_o} \times 100 \quad (4)$$

$$S_h[\%] = \frac{W_t - W_m}{W_t} \times 100 \quad (5)$$

$$M_h\ [\%] = \frac{W_m}{W_o} \times 100 \quad (6)$$

The vertical elongation E_v [%], vertical shrinkage S_v [%] and vertical shape memory ability M_v [%] were deduced from original course spacing C_o, temporary course spacing C_t and memorable course spacing C_m by equation (7)-(9) below:

$$E_v\ [\%] = \frac{C_t - C_o}{C_o} \times 100 \quad (7)$$

$$S_v[\%] = \frac{C_t - C_m}{C_t} \times 100 \quad (8)$$

$$M_v\ [\%] = \frac{C_m}{C_o} \times 100 \quad (9)$$

Each dimensional measurement was triplicated to get the average value.

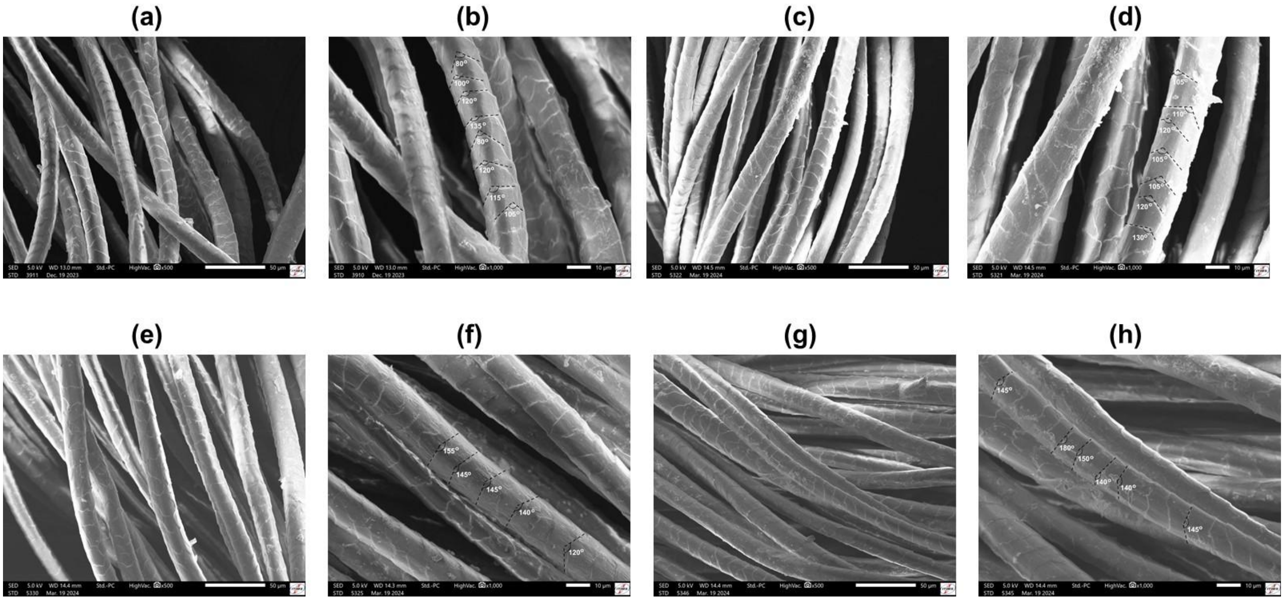

Figure 2. SEM images of wool yarn before descaling treatment (a, b); descaled with nano powder concentration of 2 g/l (c, d); 5 g/l (e, f); 10 g/l (g, h).

RESULTS AND DISCUSSION

Influence of nano powder concentration on wool descaling ability

The effectiveness of the ultrasonic descaling process with calcium carbonate nano powder (CCNP) was evaluated through the change in the sharpness of the wool fiber scales, specifically the angle formed by the two tangent lines to the two sides of the scale. **Chyba! Nenalezen zdroj odkazů.** presented a series of scanning electron microscope (SEM) images that illustrated the impact of calcium carbonate nano powder (CCNP) abrasion on the surface morphology of wool fibers. The images in **Chyba! Nenalezen zdroj odkazů.**(a-b) showed the surface of the initial wool fiber, where the scales were clearly observed with an average angle of approximately 105º.

As the CCNP concentration was increased, the abrasive effect became more pronounced. At a concentration of 2 g/l (**Chyba! Nenalezen zdroj odkazů.**(c-d)), the edges of the scales became less sharp, with the average scale angle increasing to approximately 115º. This tendency became clearer with higher CCNP concentrations, intensifying at 6 g/l with an average angle of 140º (**Chyba! Nenalezen zdroj odkazů.**(e-f)), and finally resulting in a nearly flat surface at 10 g/l with an average angle of 150º (**Chyba! Nenalezen zdroj odkazů.**G-H).

The images demonstrated that the sonification of CCNP caused an abrasive treatment that effectively modified the scales of the fiber. This effect intensified with the increase in CCNP concentration because the edges of the scales were worn and gradually lost their sharpness. The scales' loss of sharpness after descaling changed the mechanical properties of the descaled yarn, such as breaking strength and elongation, and the properties of the fabric knitted from these yarns.

Influence of nano powder concentration on breaking strength and elongation of wool yarn

The Figure 1 showed that the descaling treatment using calcium carbonate nano powder (CCNP) significantly increased the breaking strength of the wool yarn. An increase of approximately 28% was observed, from 133.4 cN for untreated yarn to 170.0 cN for yarn treated with 2 g/l of CCNP. As the CCNP concentration was increased from 2 to 10 g/l, the yarn breaking strength remained relatively stable, ranging from 160 to 170 cN. These findings contrast with a previous study by A. Ghasemi, which reported a decrease in breaking strength with increasing CCNP concentration.

The observed increase in breaking strength may be attributed to an increase in the homogeneity of the fiber's surface due to the abrasive action of the descaling process. This improved homogeneity allows the exerted force to be distributed more evenly along the fiber, thus increasing the yarn's overall breaking strength.

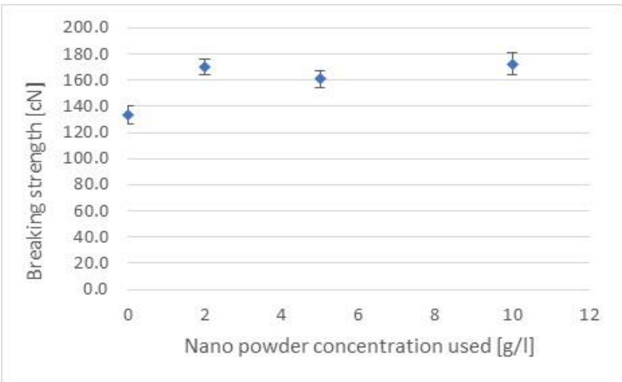

Figure 1: Breaking strength of wool yarn before and after descaling treatment with calcium carbonate nano powder.

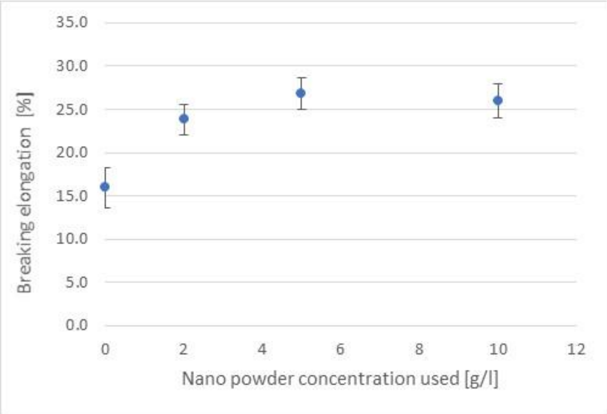

Figure 2: Breaking elongation of wool yarn before and after descaling treatment with calcium carbonate nano powder.

In contrast, in a non-homogeneous structure, force tends to concentrate at the weakest point, leading to premature breakage at a lower value than the system's expected breaking strength.

Furthermore, the decrease in the coefficient of variation (CV) for the breaking strength of the descaled yarn provides additional evidence of this enhanced homogeneity. The CV value for the untreated yarn was 16.3%, whereas it was lower for the treated yarns, ranging from 10% to 15%. This reduced deviation in the breaking strength values for the treated yarn supports the hypothesis that the descaling process leads to a more uniform fiber structure.

Figure 2 illustrates the breaking elongation of wool yarn before and after descaling treatment with calcium carbonate nano powder (CCNP). The data reveals a similar trend to that observed for breaking strength. The descaling treatment resulted in a substantial increase in the yarn's breaking elongation, rising by approximately 1.5 times from 16.0% for the untreated yarn to 23.8% for the yarn treated with 2 g/l of CCNP. When the CCNP concentration was increased from 2 g/l to 10 g/l, the breaking elongation remained relatively stable, falling within the range of 24% to 27%. The increase in breaking elongation is hypothesized to be a result of the abrasive action of the CCNP and ultrasonic treatment, which creates a more homogeneous fiber surface. This improved homogeneity allows for a more even distribution of force during stretching, thereby increasing the time to force distribution and, consequently, the breaking elongation. Further supporting this hypothesis is the significant decrease in the coefficient of variation (CV) for breaking elongation following the treatment. The CV for the untreated yarn was 46.5%, whereas it was markedly lower for the treated yarns, ranging from 22% to 24%. This reduction in the CV confirms that the descaling treatment contributes to a more uniform yarn surface. Overall, the descaling treatment improved both the breaking strength and breaking elongation of the yarn while also making it more uniform. These enhanced properties are a favorable outcome for the application of this treated wool yarn in knitted products, where good strength and elongation are essential for comfort and durability.

Influence of nano powder concentration on shape memory behavior of wool yarn

Table 1 showed the influence of nano powder concentration on the shape memory behavior of wool yarn. The data, which compared the yarn's temporary condition (warm-humid) to its initial cold-dry condition, recorded only a little change in yarn length. A slight increase in shrinkage was observed as the CCNP concentration was increased from 2 g/l (2.2%) to 5 g/l (2.8%) and 10 g/l (3.0%) during the change from the warm-humid to the cold-dry condition. Generally, the shape memory ability (*M*%) for all yarn samples, both untreated and treated, was quite good, ranging from 98.0% to 98.8%.

Influence of nano powder concentration on shape memory behavior of wool knitted fabric

Tables 2 and 3 detailed the shape memory behavior of the wool knitted fabric. The results indicated that the fabric elongated under warm-humid conditions and shrunk under cold-dry conditions in both the horizontal (wale spacing) and vertical (course spacing) directions.

Table 1: Influence of nano powder concentration on the change in yarn length.

Nano powder concentration [g/l]	**0**	**2**	**5**	**10**
Original length L_o [mm] *Storage in cold-dry condition for 24 hours*	50.0 ± 0.0	50.0 ± 0.0	50.0 ± 0.0	50.0 ± 0.0
Temporary length L_t [mm] *Expose to warm-humid condition for 30 min*	50.5 ± 0.2	50.5 ± 0.0	50.6 ± 0.0	50.5 ± 0.0
Memorable length L_m [mm] *Back to cold-dry condition for 30 min*	49.1 ± 0.1	49.4 ± 0.1	49.2 ± 0.3	49.0 ± 0.2
Elongation *E* [%] by equation (1) *Change from cold-dry (original) to warm-humid (temporary) condition*	1.0 ± 0.4	1.0 ± 0.0	1.2 ± 0.1	1.0 ± 0.0
Shrinkage *S* [%] by equation (2) *Change from warm-humid (temporary) to cold-dry (memorable) condition*	2.8 ± 0.3	2.2 ± 0.1	2.8 ± 0.5	3.0 ± 0.5

Shape memory ability *M* [%] by equation (3) *Compare the memorable to original dimension*	98.2 ± 0.2	98.8 ± 0.1	98.4 ± 0.5	98.0 ± 0.5

Table 2: Influence of nano powder concentration on the change in wale spacing.

Nano powder concentration [g/l]	**0**	**2**	**5**	**10**
Original wale spacing W_o [mm] *Storage in cold-dry condition for 24 hours*	3.2 ± 0.1	4.1 ± 0.1	4.1 ± 0.1	4.2 ± 0.1
Temporary wale spacing W_t [mm] *Expose to warm-humid condition for 30 min*	3.4 ± 0.0	4.3 ± 0.1	4.3 ± 0.1	4.4 ± 0.1
Memorable wale spacing W_m [mm] *Back to cold-dry condition for 30 min*	3.0 ± 0.0	3.9 ± 0.1	3.9 ± 0.1	4.1 ± 0.1
Horizontal elongation E_h (%) by equation (4) *Change from cold-dry (original) to warm-humid (temporary) condition*	6.2 ± 1.9	4.9 ± 1.6	4.9 ± 1.5	4.8 ± 0.1
Horizontal shrinkage S_h (%) by equation (5) *Change from warm-humid (temporary) to cold-dry (memorable) condition*	11.8 ± 1.0	9.3 ± 1.4	9.3 ± 0.9	6.8 ± 1.1
Horizontal shape memory ability M_h [%] by equation (6) *Compare the memorable to original dimension*	93.8 ± 1.0	95.1 ± 0.1	95.1 ± 1.6	97.6 ± 1.3

Table 2: Influence of nano powder concentration on the change in course spacing

Nano powder concentration [g/l]	**0**	**2**	**5**	**10**
Original course spacing C_o [mm] *Storage in cold-dry condition for 24 hours*	1.9 ± 0.0	1.8 ± 0.0	1.8 ± 0.0	1.7 ± 0.0
Temporary course spacing C_t [mm] *Expose to warm-humid condition for 30 min*	1.9 ± 0.0	1.9 ± 0.0	1.9 ± 0.0	1.8 ± 0.0
Memorable course spacing C_m [mm] *Back to cold-dry condition for 30 min*	1.8 ± 0.1	1.8 ± 0.0	1.8 ± 0.0	1.7 ± 0.0
Vertical elongation E_v (%) by equation (7) *Change from cold-dry (original) to warm-humid (temporary) condition*	0.0 ± 1.8	5.6 ± 1.9	5.6 ± 1.9	5.9 ± 2.0
Vertical shrinkage S_v (%) by equation (8) *Change from warm-humid (temporary) to cold-dry (memorable) condition*	5.3 ± 2.0	5.3 ± 1.8	5.3 ± 1.8	5.6 ± 1.9
Vertical shape memory ability M_v [%] by equation (9) *Compare the memorable to original dimension*	94.7 ± 1.9	100.0 ± 0.0	100.0 ± 1.8	100.0 ± 0

It could be seen that the wool knitted fabric elongate by warm-humid condition and shrinkage by cold-dry condition horizontally. The horizontal elongation E_h [%] was higher for un-treated wool knitted fabric (6.2%) and for the descaled fabric samples, the nano powder concentration seemed to not affect the horizontal elongation, the value of E_h [%] was around 4.8 ÷ 4.9 % for the wool knitted fabric descaled with 2 g/l, 5 and 10 g/l of calcium carbonate nano powder. Similarly, in the cold-dry condition, the horizontal shrinkage S_h [%] was also higher for un-treated wool knitted fabric (11.8 %). However, in this state, the nano powder concentration influenced on horizontal shrinkage of descaled wool fabric, the value of S_h (%) was lowest (6.8 %) for the fabric treated with 10 g/l of nano powder. The horizontal shape memory ability [Mh%] was consistently good, ranging from 93.8% to 97.6%, with the best was the fabric treated with 10 g/l of CCNP (97.6 %).

Table 3 showed a similar trend for the vertical direction, though the magnitude of change was much less. The vertical elongation in the warm-humid environment was in the range of 0% to 5.9%, and the vertical shrinkage in the cold-dry environment was in the range of 5.3% to 5.6%. Notably, the descaling treatment had a more obvious effect on the vertical dimension. The untreated fabric did not elongate vertically, while the descaled fabrics elongated by 5.6% to 5.9%. Consequently, the vertical shape memory ability (M_v) of the treated fabric was increased from 94.7% to 100%.

In general, the wool knitted fabrics demonstrated a high degree of dimensional recovery, with horizontal shape memory ability (M_h) ranging from 93.8% to 97.6% and vertical shape memory ability (M_v) ranging from 94.7% to 100%. The shape memory ability of the wool knitted fabric increased in both the horizontal and vertical directions after the descaling treatment. Notably, the vertical shape memory ability reached 100% for all wool knitted fabrics descaled with nano powder at concentrations of 2, 5, and 10 g/l.

It was observed that while the change in environmental conditions had a negligible effect on yarn length (as shown in Table 1), the wale and course spacing of the wool fabric underwent distinct changes. Hu J. et al. [9] reported that immersing wool fibers in water led to a significant decrease in fiber diameter and an increase in length (approximately 16%), with the dimensions almost fully recovering after complete drying. Their study on single-jersey wool fabric showed that after water immersion, both wale and course spacing increased, and the total fabric area expanded by about 20% compared to the dry state, with a near-complete recovery upon drying. In the current study, the change in moisture from a cold-dry to a warm-humid environment may not have been as impactful as direct water immersion, which could explain the insignificant change in yarn length noted in Table 1. Additionally, the chemical descaling agent (chlorination) used by Hu J. et al. [9] likely provided a more potent effect than the mechanical descaling method employed here. Nevertheless, the combination of moisture and temperature changes in this study was sufficient to alter the spatial configuration of the knitted loops, leading to an increase in both wale spacing (Table 2) and course spacing (Table 3). This clearly indicates that the ultrasonic descaling treatment with CCNP made the wool fabric more sensitive to changes in temperature and humidity.

It should be noted that, in comparison to the untreated fabric, the descaled wool knitted fabric exhibited greater sensitivity to environmental temperature and humidity changes in the vertical direction but less in the horizontal direction. The change in the sharpness of the wool fiber scales could be the reason of the tendency. The more concentration of CCNP the more scales' loss of sharpness. As consequence, the friction between the yarn decreased that may help the fabric returned easily to initial dimension. For thermoregulating applications, it is not only important for the fabric to return to its original shape but also for its dimensions to change significantly to accelerate thermoregulation within the microclimate zone, thereby ensuring wearer comfort during environmental transitions. Consequently, a wool rib-knitted fabric with high course density and low wale density should be considered for the design of thermoregulating apparel.

CONCLUSION

The research investigated shape memory behavior of Ne 40/1 wool yarn and wool rib knitted fabric before and after the descaling treatment. A non-toxic descaling treatment was used that based on the abrasion effect of calcium carbonate nano powder (CCNP) in ultrasonic bath.

In the scope of research (Ne 40/1 wool yarn and rib fabric knitted by this wool yarn plied by 4), with three levels of CCNP concentration used that were 2 g/l, 5 g/l and 10g/l, the increase of CCNP concentration helped to strengthen the descaling effect, which resulted in less sharp morphology of scales on the wool fiber surface. Moreover, descaling treatment also helped to increase the breaking strength and elongation of wool yarn while the CV values decreased.

With the stimuli was humidity and temperature of surrounding environment, the length of wool yarn did not change much for both original and treated yarns. However, the wool rib knitted fabric tended to elongate by warm-humid condition and shrinkage by cold-dry condition in both horizontal and vertical direction. Especially, the descaling treatment had obvious effect on the shape memory behavior of wool rib knitted fabric in vertical direction. In the warm-humid condition, untreated fabric did not elongate while descaled fabric elongate vertically with the course spacing increase by 5.6 %, 5.6 % and 5.9 % for the CCNP concentration of 2 g/l, 5 g/l and 10 g/l, respectively.

In this research, generally, the shape memory ability of wool rib knitted fabric was quite good in both directions, up to more than 93%. Descaled fabric exhibited higher shape memory ability than untreated fabric, especially in vertical direction, where the course spacing could return to 100 % of the original value. This presents an opportunity to develop thermo-regulating textile products using wool yarn that has been environmentally descaled with calcium carbonate nano powder and ultrasonic energy.

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