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REGULAR ARTICLE

Improvement of Moisture Transmission Properties of Acrylic–Cotton Blended Fabric Using Calcium Chloride-Based Desiccants: A Novel Approach

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Abstract

This research reports the results of a work intended to increase the attributes regarding moisture management of acrylic–cotton-blended single jersey fabrics. In a single-step exhaust method, the blended fabric is treated with 60% calcium chloride-based desiccant at 60 °C for 1 h. The multidirectional liquid transport behavior of treated fabric through properties such as time for wetting, rate of absorbing moisture, maximum radius of wetted area, speed of spreading the test liquid, moisture transport index, and total moisture management capacity is analyzed. The experimental results exhibit improvement in the moisture management property of the treated fabrics from 0 to 0.75. The wettability of the fabric is also enhanced as the water contact angle has reduced from 108.37° to 66.45° after the treatment. Treated samples transport the test liquid across the fabric much more quickly than untreated samples due to fabric–desiccant interaction through a strong hydrogen bond. This is characterized by an FTIR peak at 2341 cm^{-1} which gets reduced after treatment. The impact of desiccant treatment on physical properties such as color strength, fabric thickness and weight was also analyzed. The desiccant treatment shows durability up to five wash cycles equivalent to 25 home laundering cycles, dictating a great prospect of applying this method in the moisture management of cotton–acrylic-blended textiles. Moreover, the presence of randomly deposited desiccant particles on the blended fabric surface confirmed by SEM is achieved in a single step, emphasizing the versatility of this method.

Keywords Acrylic–cotton blend · Knitted fabrics · Desiccants · Chemical finishing · Moisture management

1 Introduction

Fabrics are produced to meet a range of needs in applications such as flexible conductors, sweat-wicking, water collection, and water transportation because of their simple availability, hydrophilicity, porosity, and breathability [1]. Moisture management qualities are a crucial factor in defining the level of comfort of a fabric [2, 3]. According to Hu et al., moisture management of textile material denotes a fabric's capability to regulate the flow of moisture from human skin and transfer it from the innermost layer of the textile to the surface layer [4].

Research on moisture transport in textiles has become crucial since the property of moisture transport determines how comfortable a fabric is when it is intended especially for active sport [5, 6]. The capacity of cotton fabric to absorb moisture by capillary mechanism is one of its defining characteristics [7]. However, hydrophilic fibers like cotton are not the best choice for functional applications due to their affinity for water. On the contrary, fibers that show hydrophobicity, allow for the conveyance and release of liquid by capillary wicking without the need for liquid retention [8]. Fibers that wick liquid through capillaries, such as polyester and nylon, are effective at transporting liquids and releasing them [9]. Hence, consumers are beginning to choose blend materials because of their superior characteristics, affordability, and adaptability. Knitted textiles made from blended acrylic/cotton yarns are highly sought-after these days because they offer superior quality attributes, as compared to traditional cotton outerwear [10].

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Processes such as fabric finishing and surface modification have an impact on the absorbency of textile materials [11, 12]. Surface qualities including wettability, biocompatibility, adhesive bonding, and dye sorption are often altered by chemical and physical techniques such as chemical finishing, grafting, plasma treatment, and enzymatic hydrolysis [13]. The method most commonly used to give textiles unique attributes is the chemical finishing process. Other techniques such as plasma treatment, grafting, or incorporation into the fibers' polymer are durable, but these are more sophisticated and costly technologies [14–16]. Textile chemists have exploited intermolecular bonds such as: interactions between dipoles, van der Waals forces, covalent, hydrogen, and ionic bonds as their most valuable instruments for chemical finishing [17, 18], because the success of the chemical treatment mainly depends on the stability of the chemical on the surface of the textiles [19].

Because of their inherent hygroscopic properties and low energy requirements, desiccant materials have lately been identified as a promising technological solution [20]. Materials with this kind of characteristic include diethylene glycol, calcium chloride, lithium chloride, and lithium bromide, which serve as a component in the liquid desiccant. Activated carbon, molecular sieves, alumina gel, silica gel, and titanium dioxide desiccant are examples of common solid desiccant materials [21]. These materials have a considerable capacity for absorbing moisture, ranging from 50 to 1200% of their dry weight [22].

Calcium chloride and silica gel are the most popular desiccant materials used in the humidity reduction process for absorbing moisture [23]. The textile industry has used aerogel in recent years because of its multidimensional uses. Besides all the positives, it has certain inherent shortcomings necessary to be addressed, including poor durability, volumetric shrinkage, and dust release [24]. Salt adsorbents like calcium chloride ($CaCl_2$) generally have a larger water-absorbing capability than popular adsorbents like silica gel [25, 26]. Furthermore, as there has been no evidence of chloride toxicity in humans, calcium chloride has been deemed generally safe (GRAS) based on scientific methods for both the environment and humans [27].

A previous study demonstrates calcium chloride ($CaCl_2$) has been used as an additive with polyacrylonitrile (PAN) for the preparation of filtration membranes. Findings show inclusion of calcium chloride has improved the permeability of the PAN membrane hence proving their compatibility [28]. In some recent works for improving moisture management of acrylic by Jia et al., casein was grafted with acrylic fibers after alkali hydrolysis followed by a chlorination process, and better hygroscopicity, antistatic characteristics, and spinnability were displayed by casein-grafted acrylic fiber [29, 30]. Some research shows that low-temperature plasma treatment can boost the hydrophilicity of acrylic textiles, improving their dyeability and dirt resistance [31, 32]. The enzymatic treatment can also increase the hydrophilicity of the acrylic fibers and improve dye adsorption where the nitrile hydratase enzyme hydrolyzes the nitrile groups (C=N) of acrylic fibers to the equivalent amidic groups [33, 34].

Although calcium chloride ($CaCl_2$) has been used with textile materials for enhancing the color durability of naturally dyed textiles, breaking down silk fibroin, enhancing enzyme activity, and eliminating unwanted impurities from textile wastewater [35], there has not been any research documented in the literature on using $CaCl_2$ based desiccants to improve moisture controlling properties of acrylic–cotton-blended textile materials. Besides, most manufacturers are shifting their focus towards a more economical and simple process that will effectively add finishing chemicals on fabric surfaces without hampering any of the intrinsic characteristics of fabrics. Hence, this research targets to accelerate the moisture management characteristics of acrylic–cotton-blended knitted fabrics with the help of calcium chloride-based desiccant treatment in a single-step exhaust method.

2 Materials and Methods

2.1 Materials

2.1.1 Fabric

The dyed fabric was collected from MG Knit Flair Ltd. (Mohammadi Group), Gazipur, Bangladesh for experimental purposes. An automated flatbed knitting machine from China of the mentioned details was used to produce the fabrics: gauge—12 GG, knitting width—52 in. The fabric knitting was accomplished by maintaining fixed settings, and the fabric was preserved for relaxation and conditioning at standard atmospheric conditions. The fabric specification is mentioned in Table 1.

Table 1 Fabric specification

Parameter	Relevant information
Structure	Single jersey
Composition	50% Cotton, 50% acrylic
Fabric weight	480 gm/m^2
Wales per inch	17
Courses per inch	24
Yarn count	32/2 Ne

Table 2 Physical characteristics of desiccant material

Parameter	Attributes
Physical condition	Solid
Form	Powder
Chemical composition	$CaCl_2$ > 94%/starch
Moisture absorption	200–250%
Application temperature	−20 °C to 70 °C
Nature	Hydrophilic
Water solubility	High

2.1.2 Chemicals

For fabric treatment, calcium chloride-based desiccant material (AbsorGel), manufactured by Absortech International AB, Sweden, was purchased from Abedin Equipment Limited, Dhaka, Bangladesh, and used without further modification. The detailed physical attributes of the desiccant material are listed in Table 2. No reporting of the severe toxicological impact of $CaCl_2$ has been found in the previous literature. A work reported by H. C. Badrakia described calcium chloride desiccant as a non-toxic and eco-friendly substance [36]. One way to quantify toxicity is the LD50 dose; the maximum dose will cause death 50% of the time. When consumed orally by an average individual, the LD50 for pure $CaCl_2$ is comparable to that of table salt. Besides, the air blown over the calcium chloride solution is free of any dangerous materials [37]. In this work, concentrated hydrochloric acid (37%) used was supplied by Merck, Germany, sodium carbonate used was supplied by PT Smart Lab, Indonesia, soaping agent (INDOCLEAN MFD) was purchased from Hue and Chem Global Ltd., Bangladesh, standard AATCC detergent was obtained from Epic Garments Manufacturing Company Ltd., Bangladesh and deionized water was collected from Pure Tech DM Solutions, Dhaka, Bangladesh. In this experiment, all the chemical substances were used without further purification.

2.2 Methods

Before desiccant application on cotton–acrylic-blended fabric, the dyed and finished fabric was hot-washed using non-ionic detergent (1.0 g/L) at 60 °C for 10 min to remove any adhering dirt and dust. The treatment of acrylic–cotton-blended fabric with calcium chloride desiccant (60% on the weight of fabric) was used in the experiment. The chemical solution was prepared at room temperature by dissolving the required amount of $CaCl_2$ desiccant powder in deionized water. Concentrated hydrochloric acid (HCl) (4 ml/100 ml) was added to the finishing bath. Soda ash (5 gm/100 ml) was also added to the bath. The material-to-liquor ratio was set at 1:30 (w/v) throughout the experimental work. After adding the chemicals, the fabric was loaded into the dyeing pot of the Laboratory Dyeing Machine (Eco Dyer), from Xiamen Rapid Precion Machinery Co. Ltd, Taiwan. The treatment was continued at 60 °C for 60 min. After the process was completed, the bath was drained and the fabric samples were washed using cold water. After rinsing, excess water was removed from fabrics by squeezing. After squeezing, all the test specimens were dried at 80 °C for 10 min using a Laboratory Mini Dryer from Xiamen Rapid Precion Machinery Co. Ltd, Taiwan. A graphical representation of the process has been presented in Fig. 1.

2.3 Characterization

2.3.1 Scanning Electron Microscopy (SEM)

The superficial structure of untreated and treated acrylic–cotton-blended fabric was analyzed using a scanning electron microscope manufactured by Phenom Pro Desktop SEM, Thermo Fisher Scientific Inc., USA, having a magnification range of 80–150,000x. The accelerating voltage of 5 kV was upheld throughout the experiment. Before the SEM tests, a thin film of gold coating was imparted on the specimens to make the surface conductive, using a high-resolution sputter coater (Quorum Technologies, UK, Model Q150R ES).

2.3.2 Fabric Thickness and Weight

A digital fabric thickness gauge from B-TEX Engineering, India, was employed to evaluate the fabric's thickness under a specific load according to the standard ASTM D1777-96. A round pressure foot was applied from the top to the fabric sample using the standard load, which rested on a flat anvil. Five readings were taken from each sample and the mean fabric thickness value was reported. The fabric weight was measured according to test standard ASTM D3776–96. Fabric specimens having an area of 100 cm^2 were cut using

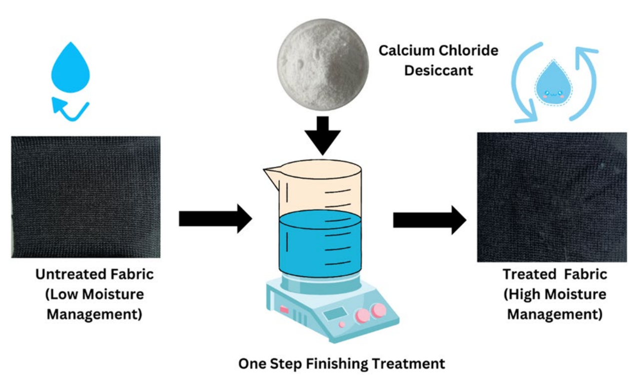

Fig. 1 Pictorial depiction of the desiccant treatment of acrylic–cotton-blended fabric

a GSM cutter. A digital analytical balance was utilized to determine the cut specimen's weight and the fabric weight per unit area was calculated according to Eq. (1) [38, 39]:

$$\text{Fabric weight}\ \left(\text{g/m}^2\right) = \text{Weight of cut specimen (g)} \times 100 \quad (1)$$

2.3.3 Fourier Transform Infrared (FTIR) Spectroscopy

An FTIR spectrometer (FT/IR-4700, JASCO Corporation, Japan) was employed for the chemical characterization of the fabric samples' interaction with desiccant materials. The absorbance of the chemical groups was measured over the range of 500–4000 cm^{-1}.

2.3.4 Color Strength (K/S Value)

The color strength is one of the essential characteristics of the dyed fabrics. The color strength of treated and untreated dyed samples was evaluated according to the Kubelka–Munk principle [40, 41]. Equation (2) derived from the principle denotes the fundamental relationship between light reflectance of fabric surface and dyestuff properties:

$$K/S = \frac{(1-R)^2}{2R} \quad (2)$$

where R is the fractional reflectance of the light, K is the light absorption coefficient, and S is the light-scattering coefficient.

The reflectance value of the samples was recorded over the range of 400–700 nm wavelengths by Datacolor 650 Spectrophotometer (Manufacturer: Datacolor, USA) using illuminant D65 with 10° standard observer. The spectrophotometer was used to take four readings of each sample after folding twice [42–44].

2.3.5 Attributes Regarding Moisture Management

A Moisture Management Tester from SDL Atlas Ltd., China bearing model: M 290 was employed for determining the moisture management characteristics, following the AATCC Test Method 195–2009 standard. The knitted specimens were enclosed by top and bottom moisture sensors in the apparatus. An 8 cm by 8 cm fabric piece was used for the test as a specimen. The layer of fabric coming into contact with the body when the clothing is put on was positioned facing the top sensor. The test sample was pumped with a fixed amount (0.15 g) of saline solution (9.0 g/L NaCl) for 20 s, and the resultant moisture transportation through the fabric was monitored for 120 s. Next, several indicators, such as the cumulative one-way transport capacity (OWTC), the time for wetting (s), speed of spreading (mm/s), wetted radius (mm), absorption rate (%/s), and the overall moisture management capacity (OMMC) of test fabrics were measured to describe the textiles' capability to manage liquid moisture [4]. Before being evaluated, every specimen was conditioned at a temperature of 20 ± 2 °C and relative humidity of $65 \pm 2\%$ in a controlled laboratory setting. Using a five-grade system as per AATCC Test Method 195–2009, the indicators are measured and graded [45–48].

2.3.6 Durability to Laundering

To be considered a viable finishing technique, the chemicals should withstand multiple washing cycles. To evaluate the laundering durability of the chemical treatment on the fabric surface, the treated fabrics were subjected to three and five laundering cycles [49]. Because of this, an established testing method AATCC test method 61–2009 (2A) was used to carry out the washing operation. According to different research, one wash cycle following this method is equivalent to five home laundering cycles [50–52]. Therefore, the five washing cycles are equivalent to 25 wash cycles. This indicates the durability of the treatment up to a significant number of wash cycles. For this test, 50 mm × 150 mm treated fabric specimens were taken and washed with 1.5 g/l 1993 AATCC Standard Reference Detergent (without optical brightener) at 49 °C for 45 min with 50 steel balls. To determine the laundering durability of the specimens, SEM, FTIR, and moisture management tests were repeated after three and five wash cycles and compared with the outcomes before washing.

2.3.7 Static Water Contact Angle

Using the standard test procedure ASTM D7334 – 08, the static contact angle between the fabric's surface and the water droplet was ascertained. The water contact angles of both treated and untreated fabric samples were measured using the "Attension Theta Lite" optical tensiometer manufactured by Biolin Scientific (Sweden). The test specimens were subjected to a drop of a predetermined volume of water (5 μL) using a needle attached to a syringe during the procedure. By taking a picture of the drop and processing it with the software, the contact angle was determined. The water contact angle was measured rapidly to avoid changes in contact angle.

3 Results and Discussion

3.1 SEM Analysis

The changes in appearance of the fabric surface after treatment with 60% $CaCl_2$ desiccant were observed through a

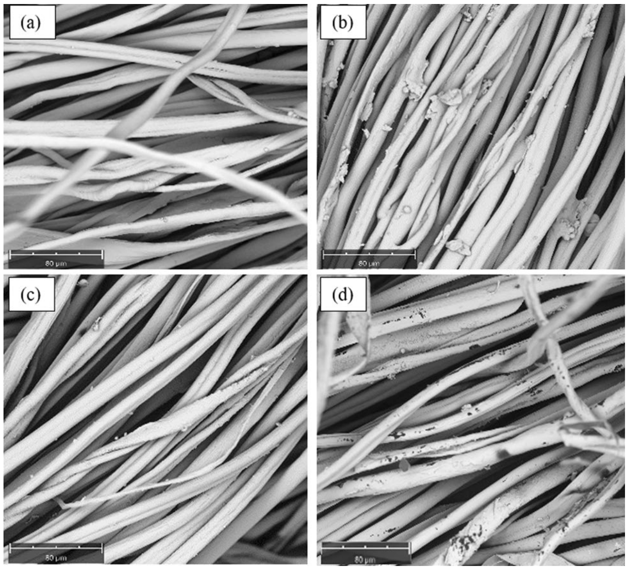

Fig. 2 SEM images of the acrylic–cotton-blended fabrics: **a** untreated, **b** treated, **c** after 3-cycle wash, **d** after 5-cycle wash

scanning electron microscope to define the consequence of chemical treatment on the fiber surface. The change of fabric surface after treatment is illustrated in Fig. 2. Figure 2a demonstrates the fiber assembly of untreated fabric with no trace of any deposits on the fiber surface. The surface topography of treated fabric indicates that there has been a remarkable difference in the surface morphology of untreated fabrics. The arbitrarily distributed adhering deposits of desiccant materials were perceived on the treated fabric surface in Fig. 2b. In case of the treated fabrics subjected to three wash cycles, as shown in Fig. 2c has a slightly different surface structure to the calcium chloride desiccant-treated sample demonstrating a smaller number of adhering particles on the fabric. This altered surface morphology suggests the mechanical force due to the collision with metal balls during the laundering cycles has affected the fabric surface. As the number of cycles increased from three to five in Fig. 2d, more adhered particles were stripped off the fiber surface. This characterization confirms the treated blended fabric can absorb a higher amount of sweat vapor from the skin and dissipate in the atmosphere owing to the moisture-absorbing desiccants present on the fabric surface.

3.2 Evaluation of Fabric Thickness and Weight

From Table 3, it can be seen that the thickness of the fabric increased slightly after desiccant treatment. The properties of knitted fabrics such as fabric weight, thickness, porosity, and pore size change according to the structural change [38]. After the initial desiccant treatment, the fabric thickness increased due to the shrinkage rather than the deposited

Table 3 Change of fabric thickness and weight after desiccant treatment and wash cycles

Condition of samples	Fabric thickness (mm)	Fabric weight (g/m^2)
Untreated	1.04	480
Treated	1.12	516.72
Treated after 3-cycle wash	1.12	520.39
Treated after 5-cycle wash	1.13	524.08

desiccant particles [39]. However, no significant difference in fabric thickness was observed after treated fabrics were subjected to different wash cycles. As mentioned by El-Kheir et al. [53], the treated and washed sample thickness results are comparable to each other. Further evaluation demonstrated that after 5 cycles of washing, fabric thickness increased slightly as the fabric surface became fuzzier [39]. This implies that chemical deposition was not the main cause of the rise in fabric thickness. Instead, the initial chemical treatment caused the fabric to shrink followed by a slight increase in thickness.

The weight of acrylic–cotton-blended knitted fabrics increased principally after the initial chemical treatment. As mentioned by Agarwal et al., fabrics often reach their maximal relaxation state after the initial chemical treatment, which causes the highest rise in fabric weight to occur [54]. Cotton fibers swell radially and longitudinally in the presence of water and alkali up to 40% of its initial volume resulting increase in fiber length. In a spiral configuration like yarn, the radial fiber swelling with minimal impact on fiber length results in yarn shrinkage. Hence, the knitted fabric shrinks adding to its weight [55]. According to the aforementioned discussion, the fabric specimens showed a gradual increase in weight after three and five cycles of wash. The maximum weight of 524.08 g/m^2 was measured for the 5-cycle washed treated fabric. The minimal variation of fabric weight of washed samples seen in Table 3 indicates that the subsequent washing treatment did not affect the fabric weight results too much. The weight of treated samples and samples after different wash cycles lies in between 400 and 600 g/m^2 which is the accepted range for commercially available protective fabrics [56]. From the overall discussion, it is prominent that the desiccant particles did not bring any significant change in the properties such as thickness and weight of treated fabric.

3.3 Analysis of FTIR Spectroscopy

FTIR spectroscopy characterizes the chemical bonds between the desiccant materials and treated fabric specimens. This approach was intended to scan the test materials and, from the peak at a particular wavenumber, offer comprehensive information on the existence of certain chemical bonds. In Fig. 3, the spectra are shown.

The FTIR band of acrylic–cotton-blended textile in Fig. 3 showed a distinctive wide peak at 3850 cm^{-1} conforming to OH-stretching, representing different states of hydrogen bonding between the fabric and water molecules [57, 58]. The weak peak present at 3770 cm^{-1} represents a complex mixture of OH and O–H···Cl vibrations that is possible to occur during the reaction of acrylic fiber with calcium chloride desiccant [59]. The strong peak at 3309 cm^{-1} also corresponds to the O–H stretching [60, 61]. In addition, the peak around 2815 cm^{-1} indicates the stretching of aldehyde hydrogen C–O–H in the cellulosic polymer of cotton fiber [62]. The peaks at 2340 cm^{-1} indicate distinctive C=N=O asymmetric stretching due to the presence of calcium-containing acrylic fiber [63, 64]. The deformation vibrations of OH- groups from adsorbed water molecules (H_2O) in cellulose can be identified by the bands at 1650 cm^{-1} because water is present in $CaCl_2$ desiccant. Different hydrogen bonds that result from the interactions of chloride ions with molecules of water in the properly hydrated form of calcium chloride are shown by the presence of some bands of asymmetric stretching of O–H and bending of H–O–H. This might be the result of O–H stretching caused by the hydrogen bonding between the molecules of water and the desiccant present in the fabric structure. Hence, different O–H vibration bands may result through hydrogen bonding of O–H···O and O–H···Cl [65, 66]. Peaks at 1450 cm^{-1} belong to $–CH_2$ bending vibration bands of aliphatic chains present in both cellulose polymers of cotton and PAN polymer of acrylic fiber [67, 68]. The small peak near around 1320 cm^{-1} corresponds to $–CH_2$ wagging vibration in cotton and PAN [69]. The sharp peak at 1006 cm^{-1} is related to the stretching of C=O due to a reaction with cellulose and water molecules [70, 71]. The surface adhesion between the blended textile and the desiccant after chemical treatment is most likely caused by the chemical interaction via H-bonding. However, insignificant changes were observed after the 3- and 5-cycle wash of the treated fabrics. In addition, a list of significant peaks obtained from the FTIR analysis is provided in Table 4 that correlate to the chemical groups of the tested specimens.

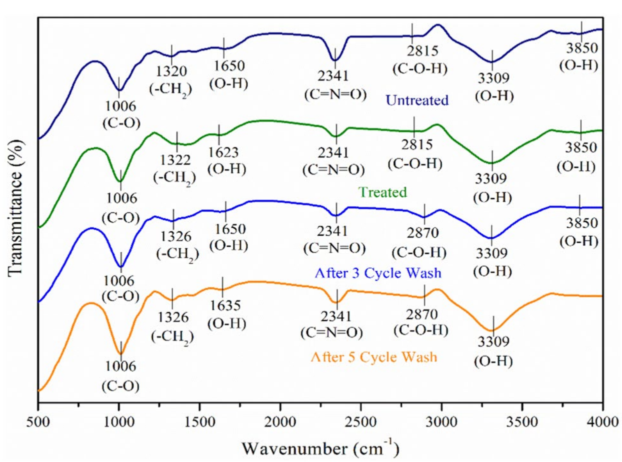

Fig. 3 FTIR spectra of cotton–acrylic-blended fabrics (untreated, treated, after 3-cycle wash and after 5-cycle wash)

3.4 Evaluation of Color Strength (*K*/*S* Value)

The color intensity in acrylic–cotton-blended dyed fabrics after the desiccant treatment and subsequent washing was evaluated and expressed using the K/S value in Fig. 4. An increased value denotes the higher depth of shade. The lower *K*/*S* value indicates color fading due to the decolorization of dye in the fabrics. The untreated fabric samples displayed the highest value of 25.33, indicating the maximum color absorbance with the minimum reflection of light from the fabric surface. On the contrary, after treatment with calcium chloride desiccant, the color strength decreased. This can occur due to the auxiliary chemicals used in the treatment. The acid used might affect the stability of the dye-cotton bond of dyed fabrics. It can initiate hydrolysis of colorants

Table 4 Detected functional groups in FTIR spectroscopy samples for treated and untreated fabrics

Wavenumber (cm^{-1})	Peak characteristics	References
3850	O–H stretching	[57, 58]
3770	O–H and O–H···Cl stretching vibrations	[59]
3305	O–H stretching	[60, 61]
2815	Stretching vibrations of C–O–H and C–H	[62]
2340	The characteristic C=N=O asymmetric stretch due to acrylic fiber containing calcium	[63, 64]
1650	Bending of O–H groups from the absorbed water molecule (H_2O)	[65, 66]
1450	Bending deformation of $–CH_2$	[67, 68]
1320	$–CH_2$ wagging and stretching vibrations	[69]
1006	C=O stretching vibration	[70, 71]

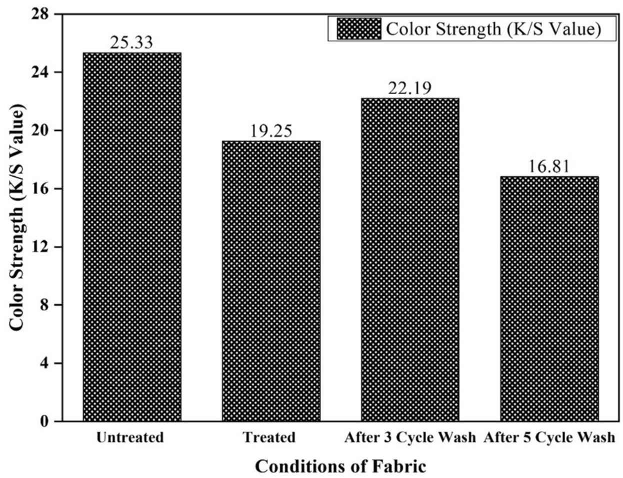

Fig. 4 Effect of desiccant treatment and wash cycles on color strength

resulting in a reduction in *K*/*S* value [72]. In addition, the deposition of micro-scaled desiccant particles might add to the color-fading effect by scattering the light from the treated fabric surface.

By far, the most popular technique for maintaining textile goods is the laundry procedure [73]. Fabrics dyed with deep colors may experience substantial color change during laundering. After washing the treated samples for up to 3 cycles, despite the loss in depth of color from untreated fabric, there is an increase in *K*/*S* value to some extent. Deep colors such as navy blue and black textiles typically fade with time, causing a color shift that may also result in an apparent boost in color intensity from the color dulling [74]. After 5 cycles of washing, there is a reduction in the *K*/*S* value to 16.81. Over the wash cycles, the subsequent washing notably lessened color strength up to 12.5% of the treated samples. Repeated wash cycles provide a longer contact duration between detergent chemicals and steel balls with dyes on the fabric surface. Therefore, more dyes are stripped off leading to color fading resulting in lowered *K*/*S* value. There is strong evidence that color fading is largely caused by the washing process rather than by use or wear. The number of washes, detergent chemicals, and mechanical agitation are some of the main reasons that cause this effect [75].

3.5 Laundering Durability

The durability of the chemical treatment was assessed by determining the resistance of the treated samples against three and five laundering cycles. As mentioned earlier, the five washing cycles are equivalent to 25 home laundering cycles, and a good number of earlier researches on the durability of moisture management finishes were concluded as sufficiently durable despite of subjected to less than 25 cycles [6, 76–78]. Moreover, after five wash cycles, the treated fabric retained its moisture management property (OMMC value: 0.635), whereas untreated fabric showed no OMMC value meaning absence of moisture management property. This indicates the durability of the treatment. The changes in the moisture transportation of acrylic–cotton-blended treated fabric with calcium chloride desiccant and going through three cycles and five cycles of wash are presented in Table 5. As shown in Table 5, after five cycles, the specimen upholds its overall moisture management capability (OMMC), meaning that the chemical treatment can be considered durable. The consideration can be supported by the fact that calcium chloride can form bonds with both the cellulosic and acrylic parts of the fabric. In the case of cotton fibers, the calcium ions (Ca^{2+}) bond with the carbonyl

Table 5 Data obtained from moisture management test (MMT) of untreated and $CaCl_2$ desiccant-treated cotton–acrylic-blended fabric after 3 and 5 wash cycles

Samples	Untreated (control)	Treated	After 3-cycle wash	After 5-cycle wash
Top				
Wetting time (s)	14.41	11.98	6.45	16.38
Rate of absorbency (%/s)	148.142	20.13	6.66	13.03
Maximum wetted radius (mm)	5	10	15	15
Speed of spreading (mm/s)	0.34	0.47	1.21	0.78
Bottom				
Wetting time (s)	120	15.91	4.02	11.60
Rate of absorbency (%/s)	0	100.49	35.59	35.95
Maximum wetted radius (mm)	0	5	15	15
Speed of spreading (mm/s)	0	0.31	1.78	0.88
Accumulative one-way transport index (%)	−332.85	717.26	637.83	476.81
Overall moisture management capability	0	0.75	0.63	0.57
Moisture management category	Poor	Very good	Very good	Good

groups of cellulose molecules using intermolecular ionic exchange and hydroxyl groups of cellulose molecules using Lewis acid/base interactions [79]. In the case of PAN polymers of acrylic fibers, the calcium ions can interact with the nitrile (C≡N) groups in PAN with the help of hydrogen bonding [80].

In addition, the cellulose molecules can be connected to Ca^{2+} ions by interacting with the carbonyl groups present in their repeat units. This is assumed to be achieved by exploiting intermolecular ionic exchange or Lewis acid/base interactions or by both [79]. Another area of Lewis acid–base interaction is the bond formation between cotton and calcium chloride due to the presence of abundant electron-donating hydroxyl ions (Lewis base) on the cotton fiber surface which act as a calcium ion (Lewis acid) binding groups during treatment with an aqueous $CaCl_2$ solution [81].

Whereas in the case of bonding with acrylic fibers, calcium ions utilize hydrogen bonds. Tang and Wu speculated that there is an interaction between Ca^{2+} ions and the nitrile (C≡N) groups in PAN, during dissipation of $CaCl_2$ aqueous solution into PAN. The C≡N groups first form hydrogen bonds with the Ca^{2+} ions during the diffusion of $CaCl_2$ solution in PAN [80]. The Ca^{2+} ion contains a vacant orbital and the nitrogen atom in the C≡N group possesses two unbounded electrons [82]. Therefore, Ca^{2+} ions can create an association by bonding with the nitrogen atom of the C≡N group of PAN.

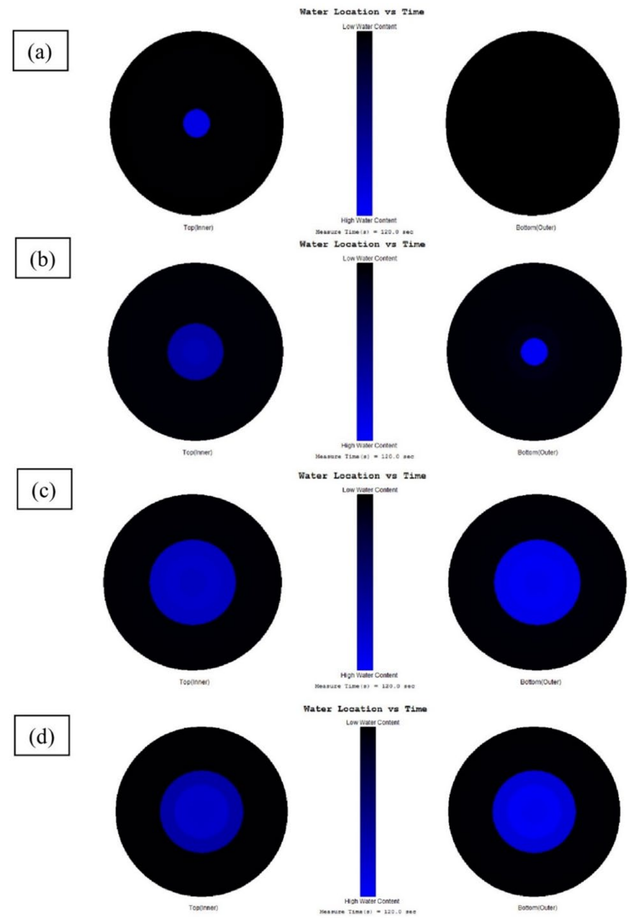

Fig. 5 Water location vs time profile of the cotton–acrylic-blended fabrics: **a** untreated, **b** treated, **c** after 3-cycle wash, **d** after 5-cycle wash

3.6 Moisture Management Property Analysis

Moisture management of textile materials often denotes the transfer of liquid and perspiration from the wearer's body to the environment across the fabric [83, 84]. The performance of any fabric's moisture management, including its total moisture management capability and one-way liquid transport capacity (OWTC), is directly connected to the thermophysiological comfort of the garment made from the fabric [85]. To define the impact of desiccant treatment on the overall moisture-managing capability of test fabric, the graphical representation of water location vs time profiles obtained from the MMT are illustrated and compared in Fig. 5, according to the MMT evaluation scale [46].

3.6.1 Effect on Time for Wetting

Both surfaces of the treated and untreated samples had their wetting times measured in seconds are given in Fig. 6. When the surface of the test sample begins to absorb water after starting the test is known as the wetting time and it is measured in seconds [86, 87].

The results regarding the untreated fabric demonstrate that the time for wetting the lower surface is significantly

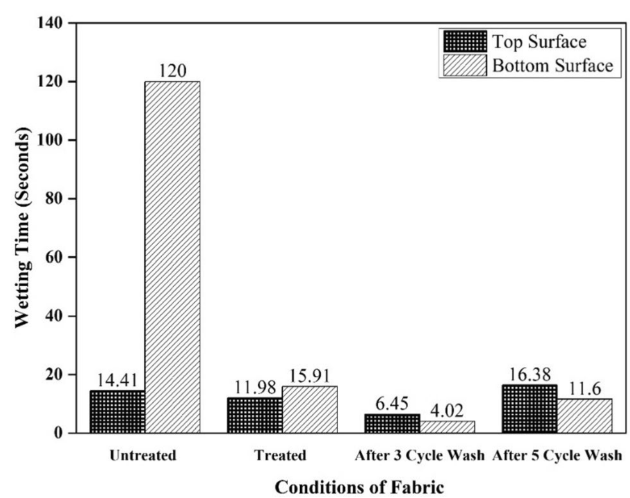

Fig. 6 Effect of desiccant treatment on time for wetting

greater than the upper surface. The high wetting time of the untreated fabric indicates the test fabric has poor moisture absorption. According to Fig. 6, the treated samples exhibit a considerable reduction in wetting time due to the surface adhesion of hygroscopic agent in the form of desiccant applied by the treatment. The reason why there is no significant difference in the top wetting time and bottom wetting time in the treated samples is that both layers of fabric contain $CaCl_2$ which is equally responsible for moisture transport. In addition, the area wetted on two sides of treated fabrics is larger compared to the untreated samples. Since cotton is a natural fiber, water molecules may adhere to its surface owing to its hydrophilic quality. As a result, cotton fibers have limited moisture transport and release capabilities and tend to retain water. Furthermore, due to their hydrophobic nature, synthetic fibers only absorb a very tiny quantity of moisture and utilize capillarity for liquid moisture transfer [86].

In addition, the effect of different wash cycles is noticeable as the top surface wetting time is slightly higher than the lower surface after three cycles and five cycles of wash. To explain this result, after being subjected to washing, the amount of surface adhering desiccants has reduced hence it takes more time to absorb the test liquid. But after washing the knitted fabric, thickness increases which improves the capillary action. Therefore, the liquid transfer is quicker through to the bottom surface of the fabric by the capillary forces. Consequently, the fabric's bottom surface becomes wetter within a shorter amount of time than its top side, and the bottom side's wetted area is greater.

3.6.2 Effect on Rate of Absorption

The rates of absorption of both surfaces are displayed in Fig. 7, indicating the average capacity of the fabric surfaces to absorb moisture [86]. The graphic illustrates how the absorption rate values increase significantly after treatment but reduce slightly after different wash cycles. Figure 7 shows that the fabrics' bottom absorption rate is often greater than the top except for the untreated fabric sample. The untreated fabric sample has an absorbency rate of zero at the bottom surface as no moisture penetrated through it. For the treated samples, the illustration shows that the fabric's bottom surface absorbed the majority of the moisture. As like, the wetting time, the desiccant material adhering to the fabric surface increases the hydrogen-bonded hydroxyl groups hence improving the moisture absorption rate, which therefore shows an enhancement in the fabric's hydrophilic qualities. The treated fabric's absorption rate increased as a result of the increased hydrophilic characteristics [88].

For all treated samples, there is a large change in the absorption rates of the two layers of fabric, indicating a slower movement of moisture from the bottom to the top

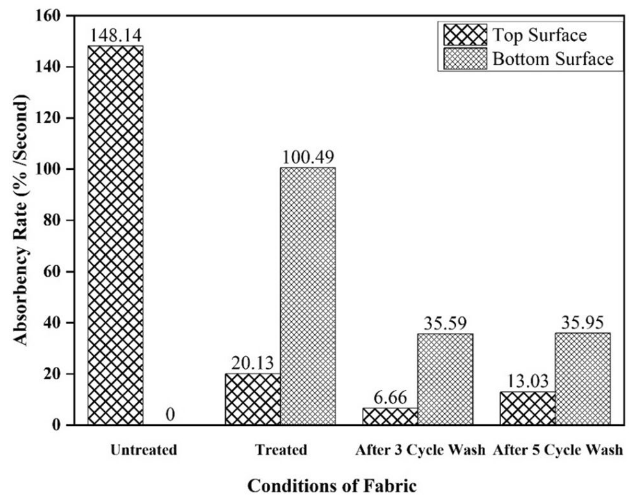

Fig. 7 Effect of treatment with desiccant on absorption rate

layer [87]. If a comparison is made between treated and washed samples, the absorption percentage per second is the highest for the treated samples without any wash. The variation has been caused by the presence of a larger amount of desiccant on the treated samples, which has led to an additional absorption percentage compared to samples that had three or five cycles of washing.

3.6.3 Effect on Maximum Wetted Radius (MWR)

In this experiment, the MWR of the untreated and chemically treated blended fabrics was also studied. The moisture profile that expands outward within the fabric plane is described by the maximum wetted radius. Excellent ratings of this index in fabric may allow for faster drying periods because of an increased wetted area [87].

Figure 8 displays the results for each sample's maximum wetted radius. It is evident from the findings that the value increases upon desiccant treatment. Untreated fabric shows reduced wetted circles, thus a smaller superficial area to carry vaporization. Due to the absorbing nature of calcium chloride desiccant, the test liquid is absorbed by the treated fabric surface more rapidly, resulting in increased moisture wicking through the material [45]. Due to the hydrophilic nature and absorbency produced by the chemical treatment, a portion of the saline liquid is engrossed and infiltrates the fiber structure, increasing the amount of moisture that spreads throughout the fabric [88]. The liquid is not soaked because of the hydrophobic characteristics of the acrylic fibers. Hence, capillary forces make it simple for the test liquid to pass through the fabric. The wetted areas on both sides of the treated fabrics after different wash cycles are very high because of this capillary action [86]. The fabric's upper layer in the test apparatus is the surface that comes into contact

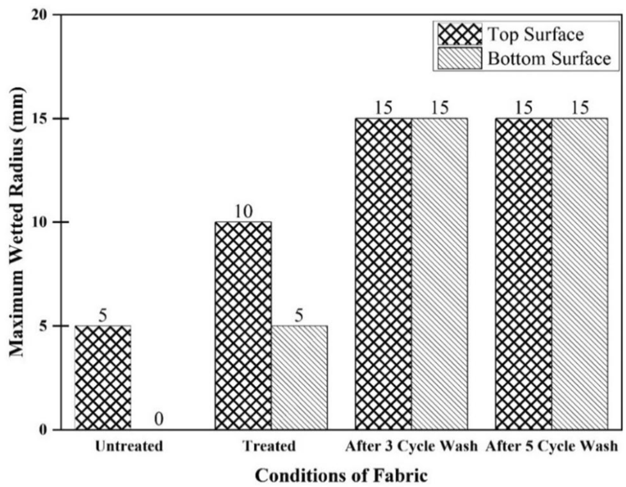

Fig. 8 Effect of desiccant treatment on MWR

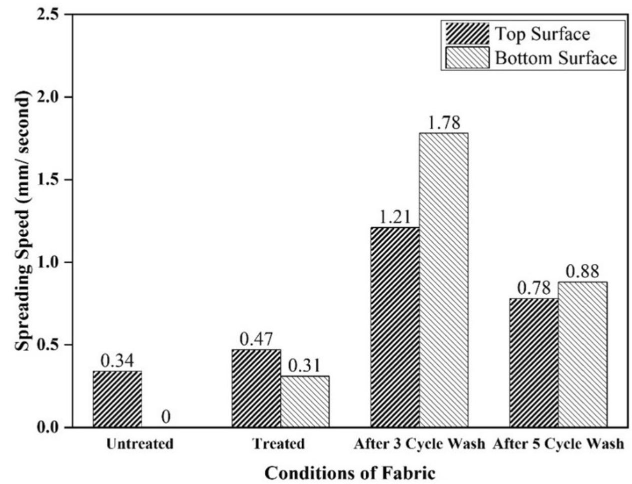

Fig. 9 Effect of desiccant treatment on SS

with the skin. According to the comfort model, the body loses heat as sweat evaporates from the skin, and this immediate heat loss from liquid sweat makes the user feel cooler [89]. Based on this explanation a conclusion can be drawn that, to have a cool feeling, a fabric that has decent absorbency can help take the moisture vapor away from the skin.

3.6.4 Effect on Spreading Speed (SS)

Figure 9 displays the spreading speed test results for both treated and untreated samples. The accumulated spreading speed of the test liquid from the place where it contacts the specimen to the MWR is known as the spreading speed expressed in mm/s [46]. The SS is measured based on the following Eq. 3:

$$SS_{top} = MWR_{top}/t_{wrt} \text{ and } SS_{bottom} = MWR_{bottom}/t_{wrb} \quad (3)$$

The time duration to attain the maximum wetted rings on the upper and lower fabric surfaces is denoted by the variables t_{wrt} and t_{wrb}, respectively [4].

It is evident from the differences in the spreading speed measurements that the treated sample's spreading speed improves. As previously mentioned, the maximum wetted radius of textiles treated with desiccant is larger, and as a result, the SS of the desiccant-treated fabric is more rapid than the untreated one. In untreated fabrics, the values of SS for both sides are inferior to the treated samples, due to the lower maximum wetted rings. These findings can be described as follows: in treated fabrics, the water is transferred by capillary forces and absorbed by the desiccants; hence, the soaked area on the treated fabric is higher, increasing the spreading speed. On the contrary, in untreated samples, a small portion of the liquid may be transported by capillary action since the majority of the liquid is engrossed by the cotton fibers. Due to the high hydrophobic characteristic of untreated fabric, a lesser amount of liquid is engrossed in the fabric. Moreover, when the fabrics are subjected to three wash cycles, the fabric changes its dimension and becomes thicker and the wetting radius increases along with the spreading speed. As mentioned by Karthikeyan, et al., the spreading speed of thicker textile materials is higher than that of thinner fabrics, possibly due to the lower porosity value of the former [45].

3.6.5 Effect on Accumulative One-Way Transport Index (AOTI)

The collective amount of moisture vapor difference between the fabric's surfaces is known as the AOTI. The one-way transmission capability of liquid through the fabric surfaces is reflected by the AOTI. The correlation between chemical treatment and the AOTI can be perceived in Fig. 10. AOTI was improved by fabric treatment with desiccant which means the fabric transfers the liquid rapidly without retaining it in the fabric [90]. The untreated fabric sample exhibits negative one-way transport capabilities, meaning that the moisture will collect on the top of the fabric surface instead of diffusing smoothly from the side next to the skin. It also indicates that there is more water on the surface on top than on the bottom. Perspiration can travel to the fabric's outer layer with ease when the AOTI values for treated textiles are positive and high. According to the data of AOTI, it is seen that the values for treated samples are more than the washed samples, meaning the treated fabric shows better moisture management ability, and the subsequent wash cycles harm the AOTI value of the treated sample [45]. The high value of AOTI in treated fabrics is due to the change in surface

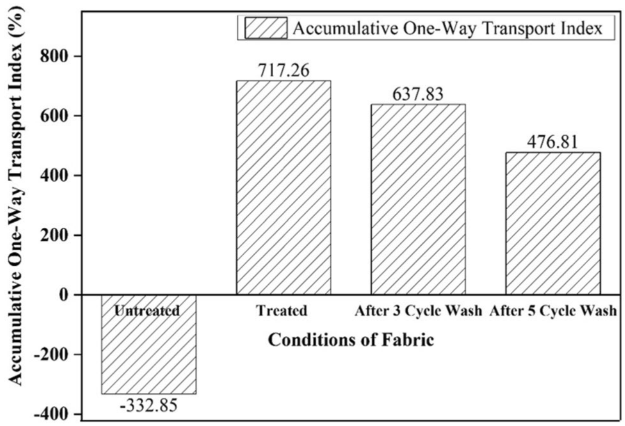

Fig. 10 Effect of desiccant treatment on AOTI

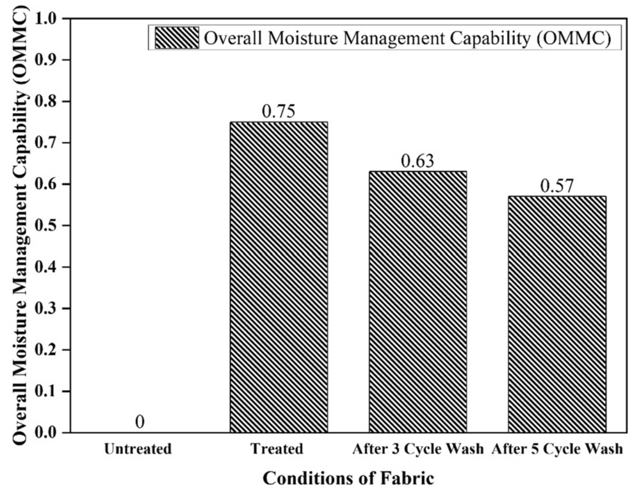

Fig. 11 Effect of desiccant treatment on OMMC

morphology of treated fabrics with calcium chloride desiccant. In addition, fabric thickness may have had an impact on the AOTI. The effect of change in fabric thickness due to wash cycles might be responsible for showing poor moisture transfer [91, 92]. Concerning the AOTI, the treated samples are regarded as 'very good', whereas the untreated samples are rated as 'very poor [4].

To develop activewear products for cold climates, desiccant was used as a moisture management finishing chemical for acrylic–cotton-blended textiles. $CaCl_2$ desiccant is a very good moisture absorber, though the possibility of absorption of moisture from the highly humid environment into the fabric can be ignored as the desiccant-treated fabric is intended for moisture management in cold weather. In cold and wet weather, to maintain prolonged physical activity in occupations such as cold storage work, winter traveling, tourist guides, and winter sports, clothing must be adaptive to minimize perspiration [93]. For sportswear and activewear where a lot of sweat is generated, 100% cellulosic fibers are not suitable as they absorb moisture into the fiber structure and get heavy [94]. Hence, a blend of cotton and acrylic fibers has become the choice of interest for this research. The avoidance of moisture penetration into the fabric from the highly humid environment can be explained through diffusion. In such conditions, moisture vapor can remain both in the adsorbed state on the fiber surface and in the entrapped state between the fiber voids [95]. The movement of vapor that has been adsorbed on the surfaces of fibers is known as surface diffusion. Diffusion occurs due to the affinity of water vapor to the hydrophilic fibers like cotton until it dissipates. However, the surface diffusion does not contribute to the total moisture transport if the diffusion is restricted only to the surface of the outer layer of fabric [96]. As the treated fabric is intended for cold weather application, the possibility of moisture absorption onto the inside of the fabric from the outside can be mitigated through the surface diffusion of moisture by cotton fibers of the fabric.

3.6.6 Effect on Overall Moisture Management Capability (OMMC)

The term OMMC is an index that measures three particulars of a fabric's moisture management performance measurements: the rate at which the bottom side absorbs moisture, the capacity of one-way liquid transport, and the maximum SS [4, 46, 87, 97]. The high OMMC value indicates high moisture transfer, hence, the fabric is more capable of moisture management [90]. To provide a clear overall assessment and outcome for the liquid moisture management attributes, every sample is categorized according to the grades and values as follows: (0–0.2: poor, 0.2–0.4: fair, 0.4–0.6: good, 0.6–0.8: very good, >0.8: excellent) [98]. After comparing the outcomes of the mentioned parameters with the standard, the untreated fabric showed poor moisture management properties, whereas the treated fabric showed very good moisture management abilities. However, after three and five wash cycles, the performance has degraded to some extent as the sample has shown good moisture management abilities after 5 wash cycles. The comparative OMMC values are illustrated graphically in Fig. 11. As per the manufacturer-provided grading scale, the desiccant-treated fabric was categorized as water penetration fabric with a large spread area, quick spreading, quick wetting, quick absorption, and outstanding one-way transport capabilities, whereas the untreated fabric was deemed as waterproof fabric with properties such as very low rate of absorption, slow spreading speed, no one-way transport capability and no moisture absorption [46].

3.7 Analysis of Water Contact Angle (WCA)

The wetting process of a solid material is studied using contact angles. The contact angle of heterogeneous structures, such as textiles and clothing, is affected by factors such as molecular positioning, roughness of the surface, polar structures, absorbent layers, pores, swelling, and interfacial tension [99]. The fabric's wettability capacity is directly correlated with the contact angle measurement. High wettability is indicated by a low contact angle [100]. The contact angle also determines the wicking behavior. Increased rates of wicking are caused by a smaller contact angle [101, 102]. The average static contact angle values of the test specimen are reported in Fig. 12. It can be observed that the untreated sample has the highest WCA value of 108.37° (more than 90°), indicating their hydrophobic property and low wettability. On the other hand, the treated fabric shows a WCA of 66.45°, indicating that the fabric is hydrophilic and easily wettable [103].

Figure 13 exhibits captured images of water droplets on the sample fabrics, 10 s after the water drop first made contact with the fabric's surface [104]. The untreated sample absorbs the least amount of water reflecting its hydrophobicity. However, the treated fabric has a lower contact angle showing its hydrophilic nature and high wettability. This result shows the enhanced hydrophilic character of desiccant-treated samples. After placing a water droplet on the fabric samples, it is absorbed completely within 1 s in the case of the three- and five-cycle washed treated samples; hence, there are no droplets present on the fabric samples as shown in Fig. 13c and d and no contact angle was recorded. The surfaces of textile fibers are not flawless and various factors such as the thickness of fabric, areal density, amount of twist, yarn types, and count, variation in pore size, roughness of the surface, heterogeneity, and the ability to absorb liquids can complicate the wetting phenomena and alter the surface energy [105]. The treated fabric having deposits of desiccant materials on the fabric adds micro-roughness on its surface. As a result, the surface of treated fabrics is not very flat, smooth, or uniform. Therefore, the contact angle measured is lower after the fabric has been subjected to desiccant treatment [106].

In the case of the samples after three and five wash cycles, no contact angle could be recorded as the droplet is instantly absorbed by the specimen. This is explained by the fact, that tightness and surface roughness changes the contact angle. Because of the surface's compactness, tightly knitted fabrics exhibit greater contact angles than loose ones [38]. When subjected to subsequent wash cycles, the tightness of the fabric gets reduced and the surface becomes rougher. The fabric pores become wider, making it easier for water to get absorbed. Hence, the water droplet placed during the WCA test gets absorbed within 1 s of placing it on the fabric surface.

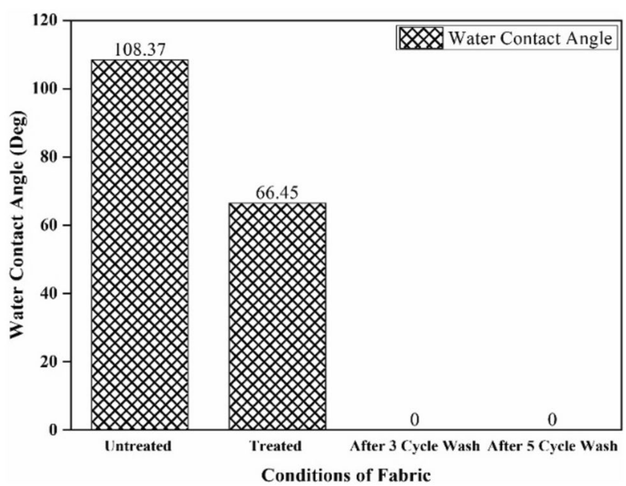

Fig. 12 Effect of desiccant treatment on water contact angle measurement

4 Conclusion

This research principally emphasizes improving the moisture management behavior of the acrylic–cotton-blended fabrics in a 50:50 blend ratio. The potential application of calcium chloride-based desiccant on cotton–acrylic–blended fabric surface was investigated for the development of a fabric fit for active wear in cold weather with improved moisture management properties. Generally, most of the moisture management finishes are applied as a coating in pad-dry-cure method exploiting high curing temperature, a higher number

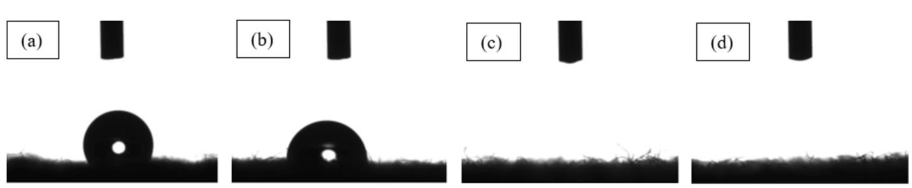

Fig. 13 Microscopic images of water droplets for contact angle measurement on different fabric samples: **a** untreated; **b** treated; **c** treated sample after 3 wash cycles; **d** treated sample after 5 wash cycles

of chemicals, and multiple processes. This method can be a simple and cost-effective alternative, as the desiccant chemical is applied at a lower temperature in a single-step batch method using an aqueous medium.

The morphological analysis of the desiccant-treated fabric through SEM revealed a fine layer of randomly deposited desiccant particles all over the fabric surface. This desiccant particle layer is said to be responsible for providing effective moisture management. Moreover, it was found that the finishing process rather than the desiccant particles had negligible impact on the thickness and weight of the treated fabric. However, as the treatment was performed on dyed fabric as a chemical finishing, the color strength value of the treated samples degraded to some extent. Though the cotton–acrylic-blended fabrics are not inherently good moisture absorbers, the addition of desiccant particles had an improved effect on the moisture absorbency and moisture transportation properties. Substantial interfacial hydrogen bonding between the $CaCl_2$ desiccant and the treated fabric was identified during the chemical evaluation of treated specimens using FTIR, which induced a durable finish on the fabric surface.

According to the results found in MMT, it can be stated that, as the treatment is done, the desiccant affects moisture transmission properties. It reduced the wetting time of both the top and bottom, and increased the bottom absorbency rate, spreading speed, cumulative OWTI (%), and the fabric's ability to manage moisture. The addition of desiccant moved the moisture quickly from one side of the cloth to the other without allowing it to gather within the structure. It means that with the treatment with desiccant, it takes a lesser amount of time to wet acrylic–cotton knitted fabric. Upon reviewing the study's findings, the highest OMMC value was achieved with treated fabric and the minimum with untreated fabric whereas the treated fabric samples subjected to different wash cycles harmed the overall moisture management property.

This finding suggests that the treated textiles have improved moisture management qualities and rapid water transfer capabilities than untreated and washed samples. For the untreated fabric samples, the fact that the AOTI values were found to be negative indicates that the untreated acrylic–cotton-blended knitted fabrics do not have any moisture management properties and keep the liquid on their surface which will provide discomforting feelings to the wearer. Based on the OMMC values, the untreated samples were evaluated as "poor" in moisture management.

In addition, the high AOTI and OMMC values suggest that to offer clothing comfort during vigorous functioning, the treated specimens may efficiently hold substantial volumes of bodily sweat and dissipate it into the atmosphere. The WCA measurement of the fabric samples after treatment also indicates that the wettability of the samples has increased as the contact angle of the treated fabric has reduced significantly. The overall outcome of this research suggests calcium chloride-based desiccants as a potential material responsible for a new approach in developing improved moisture management fabrics made from cotton–acrylic blends.

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Data availability The data supporting the findings of this study will be available from the corresponding author upon request.

Declarations

Conflict of Interest The authors report no conflicts of interest regarding the publication of this research work.

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