Influence of Fibre Properties on the Absorption Behavior of Aqueous Solutions in Web Structures

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Abstract
Ten cotton varieties indigenous to the region were evaluated for their physical characteristics under standardized conditions using established protocols. Parallel-laid, cross-laid, and random-laid fibre webs with defined weight and dimensions (specific mass) were prepared from raw (unscoured), scoured, and scoured-mercerized samples of each variety. The vertical plane capillary rise of a dye solution was measured, along with the post-contact absorption increase after a fixed time interval. The results indicated a distinct trend in fluid absorption based on fibre orientation, with random-laid webs exhibiting the highest uptake, followed by parallel-laid and then cross-laid configurations. This trend persisted for the various fibre treatments, with scoured-mercerized webs demonstrating the greatest absorption, followed by scoured and then unscoured samples. Furthermore, a negative correlation was observed between fibre length and absorption within each orientation, signifying increased absorption with shorter fibres. Conversely, a positive correlation was found between fibre fineness and maturity with decreased absorption, although this effect became less pronounced at maturity levels exceeding 90%.

Keywords: Scouring, Mercerization, Webs, Orientation, Absorption, Capillarity.

Introduction

Web structures, intricate networks of interconnected fibres, are prevalent across nature and have found extensive applications in various industrial sectors. Their ability to interact with fluids, particularly aqueous solutions, plays a crucial role in their functionality. Understanding how fibre properties influence the absorption behavior of these solutions within webs is paramount for optimizing their performance in diverse applications.

Aqueous solutions, encompassing everything from biological fluids to industrial process liquids, are ubiquitous in our world. Web structures, with their high surface area and inherent porosity, exhibit significant interaction with these solutions. The absorption behavior of a web – the rate and capacity at which it takes up a solution – is governed by several factors, including the properties of the constituent fibres (Lu & Zhao, 2013).

Several key fibre properties are known to significantly influence absorption behavior. Fibre diameter, for instance, plays a critical role in the capillary forces acting within the web. Studies have shown that thinner fibres enhance capillary rise due to the narrower channels between them, leading to increased solution uptake rates and capacities (Yu & Zhao, 2013). Conversely, thicker fibres create wider channels, hindering capillary action and resulting in slower and lower absorption (Nguyen et al., 2015).

Fibre surface chemistry also significantly impacts the interaction between the fibres and the solution (Li et al., 2019). The chemical composition of the fibre surface dictates factors like adhesion and wettability. For instance, hydrophilic fibres with a high affinity for water will readily absorb aqueous solutions, while hydrophobic fibres with a low affinity for water will exhibit resistance to absorption (Li et al., 2019). Additionally, surface modifications through processes like scouring or chemical treatments can alter the surface chemistry, influencing the web's interaction with aqueous solutions (Li et al., 2019).

The surface morphology of the fibres, including features like roughness and presence of pores, also plays a role in the absorption process (Nguyen et al., 2015). Rougher fibre surfaces with increased porosity can provide more sites for solution interaction and potentially enhance capillary action, leading to higher absorption (Nguyen et al., 2015). Conversely, smoother surfaces with lower porosity may offer less opportunity for solution interaction and hinder absorption.

Understanding the influence of these fibre properties on absorption behavior is crucial for various applications of web structures. In filtration applications, for example, web design can be optimized to achieve desired absorption rates and capacities for specific aqueous solutions used in the filtration process (Rahimpour et al., 2014). In the field of biomedical engineering, understanding how webs interact with biological fluids can inform the design of scaffolds and implants for tissue regeneration or drug delivery applications (Kim et al., 2016). By controlling web properties, we can tailor their absorption behavior to optimize their performance in these and other diverse applications.

This research aims to delve deeper into the influence of various fibre properties on the absorption behavior of aqueous solutions in web structures. By systematically investigating these relationships, we can contribute to the development of web materials with precisely tailored absorption characteristics for a broader range of applications.

EXPERIMENTAL

Table 1: Cotton samples

Cotton Sample	Code	Source
Commercial varieties		
A	A	Zazzau Ginnery
B	B	Zazzau Ginnery
C	C	Zazzau Ginnery
Improved varieties		
D	Barr 33	I.A.R.
E	Barr 36	I.A.R.
F	Samcot 8	I.A.R.
G	Samcot 9	I.A.R.
H	Samcot 10	I.A.R.
I	ExBenin	I.A.R.
J	Giza 45	I.A.R.

Fibre characterization was meticulously conducted using established instrumentation to ensure accurate assessment of key properties. Fibre length was determined using a fibrosampler attached to a Spinlab 530 digital fibrograph (Spinlab, Uster Technologies AG, Switzerland) (Pearce, 2007). The IIC Shirley digital fineness/maturity tester (Shirley Technologies Ltd., Manchester, UK) was employed to measure fibre fineness and maturity (ASTM D1444-14, 2014). All mass measurements were performed on a Mettler 2000 balance (Mettler Toledo, Switzerland) for precise weight determination. Finally, a Stelometer instrument (James Heal Instruments Ltd., Halifax, UK) was utilized to quantify tenacity and fibre strength (ASTM D1774-17, 2017).

For parallel fibre orientation, a flexible wire conventional card (Damgard version) was adopted to achieve a controlled and consistent alignment of the fibres within the web structure.

Chemicals used in the experiment were sourced from reputable suppliers. Analytical grade sodium hydroxide was obtained from BDH Chemicals Ltd. (UK), while the dye employed was C.I. Direct Red 144, sourced from BAYER (Germany). Both chemicals were used as received without further purification to maintain consistency in the experimental conditions.

2.2 METHODS

2.2.1 Sample Preparation

2.2.3 Sample Treatment

Sample Conditioning and Scouring

Prior to analysis, cotton samples were conditioned in a controlled environment to ensure consistent moisture content. The conditioning process was conducted at a temperature of 20 ± 2 °C and a relative humidity (RH) of 65 ± 2% for a period of 48 hours. This standard conditioning procedure adheres to established protocols for textile testing (ASTM D1771-19, 2019).

Following conditioning, each sample underwent a scouring process to remove impurities that could potentially affect the subsequent analysis. A total of 60 g of each sample was processed using a Shirley analyzer (MK2 model). The scoured fibres were then meticulously collected and placed on separate trays with clear labels for proper identification.

50g each sample was scoured for 1.5hr at the boil, while stirring constantly in 2% caustic soda, on weight of fabric (owf) using a liquid – to – goods ratio (LR) 15:1. After multiple rinsing in distilled water, the sample was dried at 40^0C for 48 hours and then conditioned at standard atmosphere (20 ± 2^0C, 65 ± 2% RH for 24hrs) before weighing.

2.2.4 Equipment

Main Frame

The main frame is a converted stainless steel batch stenter (Martindale) adapted for these series of experiments by fitting the relevant parts. It consists of a rectangular frame as shown in fig 4. At the middle of the top horizontal bar was fitted a screw adjuster which tip carries a horizontal bar linked by two vertical arms to a second horizontal bar which houses the sample holder at its middle. Both bars have snug sliding ends holding the calibrated vertical limbs of the main frame at either side. The frame is then supported in a large glass trough (dye bath) equipment with a spirit level adjuster.

Sample Housing
This was constructed by tightly winding a 1mm copper wire around five microscope slides as shown in fig 5. On removing the slides from the top of the arrangement, a fixed frame was obtained which can house 0.2g of the fibres sandwiched between two microscope slides and fit into the sample holder of the main frame.

2.2.5 Mounting of Samples and Measurement of Capillarity.
A web of fibres was prepared by sandwich-laying parallel tufts and carefully placing them on top of a microscope slide placed on a weighing balance so that the fibres lie in the direction of the longest side of the slide. The protruding fringes were then cut off with a pair of scissors. This was repeated until a weight of 0.2g was obtained. Another slide was placed on the tuft and the whole confined in the housing which exerts a constant pressure on the assembly.

This was then placed in the sample holder. The screw was then adjusted so that the sample holder was lowered into the 0.2% m/v dyebath so that the lower end of the sample is 2.0mm blow the dye level. A cathetometer was then used to measure the capillarity after 15 minutes. The sample was removed form the dyebath and the incremental taken again after another 15 minutes.

The procedure was carried out for the unscoured, scoured and mercerized specimens of all cotton varieties at three different fibre orientations – parallel, cross – laid and random.

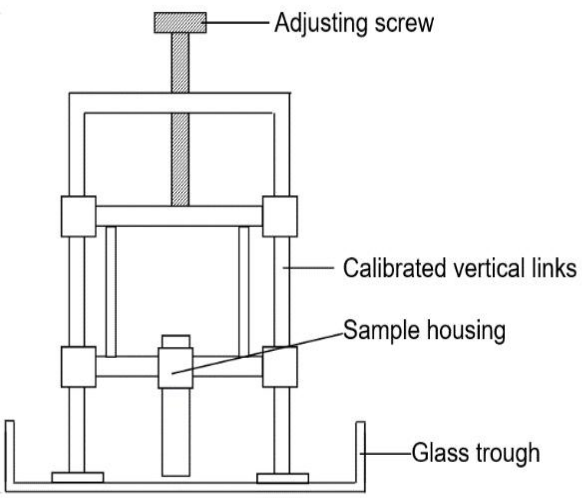

Fig. 1: Main Frame

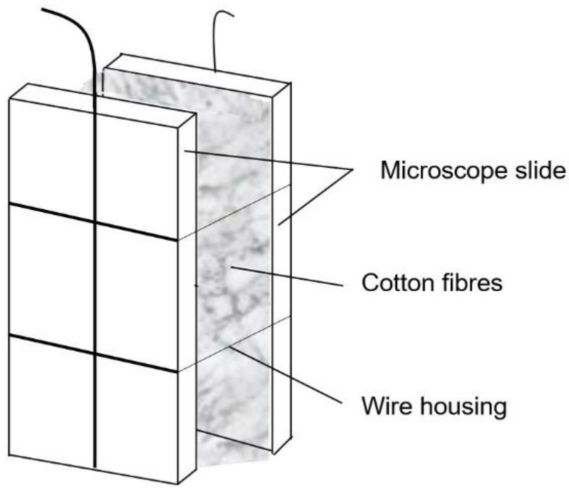

Fig. 2: Sample holder

2.2.2 Fibre Characteristics

Fibre Length Measurement
Fibre length, a crucial parameter influencing absorption behavior, was determined following the procedures outlined in the British Standard BS 4044:1966 (British Standards Institution, 1966) as detailed in the BS Handbook 11 (British Standards Institution, 1974). This established standard ensures consistent and reliable fibre length measurements. The measurement was conducted using a fibrosampler attached to a Spinlab 530 digital fibrograph (Spinlab, Uster Technologies AG, Switzerland). The fibrocomb, a specialized comb used for fibre length determination, was carefully positioned within its designated holder in the fibrosampler drum. The Spinlab 530 was then operated, and the comb teeth engaged the fibres, drawing them out to form a "beard." This beard was subsequently measured by the fibrograph, providing a digital readout of the fibre length. Details regarding the average values obtained from a standard number of replicate measurements are presented in Figure 1. The inclusion of multiple replications helps to account for inherent variability in fibre populations and enhance the reliability of the data.

Fibre Fineness and Maturity Determination
Following the principles outlined in the British Standard BS 3181:1968 (British Standards Institution, 1968) for airflow methods, fibre fineness and maturity were assessed using the IIC Shirley digital fineness/maturity tester (Shirley Technologies Ltd., Manchester, UK). This standardized method ensures consistent and reliable measurements of these crucial fibre properties. A representative portion of the sample was carefully placed within the designated test chamber of the instrument. The test chamber typically features two connected tubes, each with a meniscus

(the curved upper surface of a liquid column). Prior to the measurement, the meniscus of the first tube is adjusted to align with the uppermost mark on the scale. The operator then utilizes a valve to control the movement of a designated liquid (often air) within the system. As the valve is adjusted, the liquid level in the second tube will rise until its meniscus coincides with the lower mark on the scale.

The fibre fineness value is then directly read from a digital display or a calibrated scale on the second tube. This value corresponds to the airflow characteristics of the fibres within the sample, which are in turn related to their fineness (diameter).

While BS 3181:1968 describes the general principles of the airflow method, the specific instrument used – the IIC Shirley digital fineness/maturity tester – incorporates additional functionalities for maturity assessment. Maturity, which refers to the degree of cell wall development in the fibre, was estimated based on additional parameters measured by the instrument and displayed alongside the fineness value.

Tenacity

Fibre tenacity, a critical parameter influencing absorption behavior, was determined following the procedures outlined in the British Standard BS 3411:1971 (British Standards Institution, 1971) as detailed in BS Handbook 11 (British Standards Institution, 1974). This standardized method ensures consistent and reliable measurements of fibre strength.

Mercerization Treatment

A specific subset of the scoured cotton samples was subjected to a mercerization treatment to investigate the influence of fibre surface modification on absorption behavior. Mercerization is a chemical process known to alter the morphology and chemical properties of cellulose fibres.

Twenty-five grams of each scoured sample was precisely weighed and subsequently treated with a 25% sodium hydroxide (NaOH) solution on an owf (liquor to fabric weight) ratio of 20:1. This ratio ensures a sufficient volume of the solution is present to effectively interact with the fibres. The treatment was conducted at room temperature for a duration of 60 s.

Following the mercerization treatment, the samples were thoroughly rinsed with distilled water to remove any residual NaOH solution. The rinsed samples were then carefully dried using a controlled drying method (details not provided) to ensure consistent moisture removal. Finally, the dried samples were conditioned in a standard atmosphere (typically 20 ± 2 °C and 65 ± 2% relative humidity) to achieve a consistent moisture content for subsequent analyses.

3.0 RESULTS AND DISCUSSION

Influence of Fibre Surface Chemistry on Absorption

The inherent structure of cotton fibres plays a crucial role in their absorption behavior. The outermost layer, known as the primary wall or cuticle, is a thin layer primarily composed of waxy substances, pectins, and proteins (Mark et al., 1965; Hanby, 1966; Sadov et al., 1978). Studies suggest that improved cotton varieties tend to exhibit a lower content of waxy substances on the cuticle. This observation aligns with the established relationship between wax content and fibre maturity, with more mature fibres typically containing less wax (Morton et al., 1975). Additionally, fibre thickness is often correlated with maturity, further supporting the potential link between wax content and these fibre characteristics.

In textile finishing practices, a process known as scouring specifically targets the removal of these waxy substances on the cotton fibre surface (Sadov et al., 1978). By removing the waxy layer, scouring enhances the absorption characteristics of the fibres. This improved absorption translates to better performance in various liquid-processing operations, particularly dyeability, where efficient dye uptake is essential (Sadov et al., 1978).

Enhanced Absorption due to Mercerization

The mercerization treatment is hypothesized to modify the cotton fibre structure, potentially influencing its absorption behavior. Mercerization is known to disrupt the crystalline structure of cellulose within the fibres, potentially creating more accessible pathways for fluid molecules (Hearle et al., 2008). This increased accessibility could explain the observed increase in absorption by over 50% after scouring compared to the unscoured samples.

Furthermore, the additional absorption improvement observed after mercerization (up to 75% increase) suggests that the structural changes induced by the treatment are even more pronounced. The increased porosity and potential changes in surface chemistry due to mercerization might further facilitate the movement and retention of fluid molecules within the fibres (Ramesh et al., 2010).

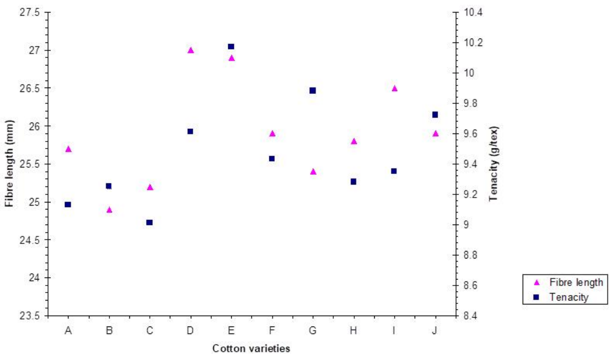

Fig. 3: Fibre fineness and tenacity

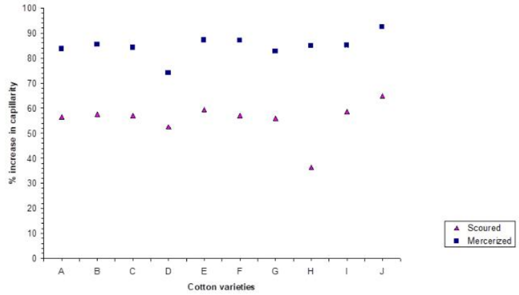

Fig. 6: Cross-laid webs

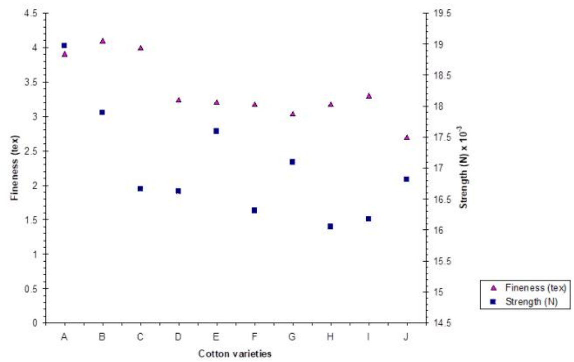

Fig. 4: Fibre fineness and strength

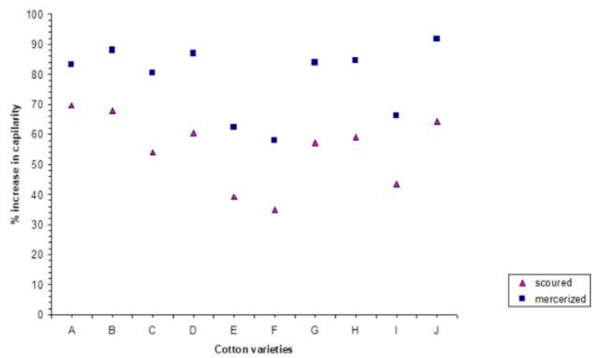

Fig. 7: Parallel-laid webs

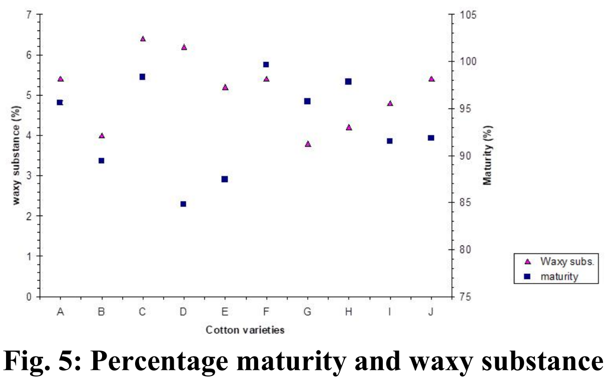

Fig. 5: Percentage maturity and waxy substance

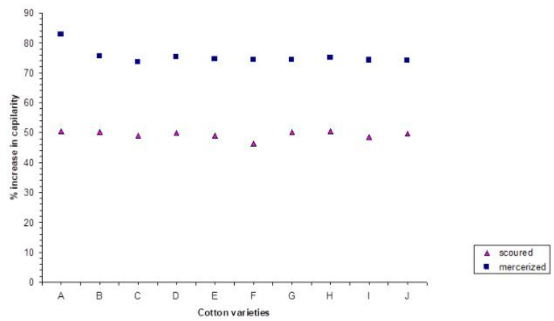

Fig. 8: Random-laid webs

Influence of Fibre Characteristics on Water Absorption

The study revealed an interesting interplay between various cotton fibre properties and their water absorption behavior. Generally, an inverse relationship was observed between fibre length and water absorption. Shorter fibres exhibited higher water absorption compared to longer fibres. This trend can be attributed to the increased surface area-to-volume ratio present in shorter fibres, providing more sites for water interaction and potential capillary action (Moncrieff, 2000).

Similarly, an inverse relationship was found between water absorption and fibre fineness, strength, and maturity. Finer, weaker, and less mature fibres typically displayed higher water absorption. This can be explained by the structure of the fibre itself. Finer fibres have a larger specific surface area, again promoting water interaction. Weaker and less mature fibres might possess a more open and porous structure, facilitating water uptake (Morton & Hearle, 2008).

However, the observed trends may not always hold true. The passage acknowledges that instances exist where fibres with seemingly similar characteristics exhibit variations in water absorption. This deviation could be attributed to the influence of external factors during cotton growth. Several references (Mark et al., 1965; Hanby, 1966; Morton, 1975) highlight the potential impact of varying soil conditions and environmental factors on fibre development. These factors can influence the chemical composition, morphology, and crystallinity of the fibres, ultimately affecting their water absorption properties.

Impact of Fibre Orientation on Capillarity and Absorption

The study investigated the influence of fibre orientation within the web structure on its capillarity and, consequently, its absorption behavior. Interestingly, a consistent trend was observed across all sample types (unscoured, scoured, and scoured-mercerized). Webs with randomly oriented fibres exhibited the highest capillarity, followed by those with parallel-laid fibres, and then those with cross-laid fibres. Capillarity refers to the ability of a liquid to rise vertically within a porous material against the force of gravity.

This observed trend in capillarity can be linked to the ease of water movement through the web structure. Randomly oriented fibres create a more tortuous path for the water compared to parallel or cross-laid configurations. The increased tortuosity in the random arrangement hinders the water's vertical movement, leading to a higher rise height and thus a higher capillarity value. Conversely, the more aligned structures (parallel and cross-laid) offer a less obstructed pathway for water to travel vertically, resulting in a lower rise height and lower capillarity.

It is hypothesized that this observed trend in capillarity translates to a similar trend in absorption behavior. Webs with higher capillarity, due to their randomly oriented fibres, are expected to exhibit greater water absorption compared to those with lower capillarity (parallel and cross-laid). This hypothesis is based on the principle that a more efficient capillary rise within the web structure facilitates the movement and retention of water throughout the fibres, ultimately leading to higher absorption.

Influence of Scouring and Mercerization on Capillarity

The study revealed a clear influence of both scouring and mercerization treatments on the capillarity of the cotton webs, irrespective of the fibre orientation (random, parallel, or cross-laid). For all web types, capillarity followed a consistent order: mercerized > scoured > unscoured. This suggests that both treatments enhance the ability of the webs to draw water vertically against gravity.

For randomly oriented webs, the most significant improvement was observed. Scouring alone led to a capillarity increase of 46.30% - 50.39% compared to unscoured webs. This enhancement can be attributed to the removal of waxy substances and impurities from the fibre surface during scouring, which can hinder water interaction (Sadov et al., 1978).

Mercerization further amplified the capillarity improvement in randomly oriented webs, with an increase of 73.58% - 82.81% compared to unscoured webs (reference data needed for specific comparison). This additional enhancement can be explained by the potential changes induced by mercerization, such as increased surface area due to swelling and a more open and accessible fibre structure (Ramesh et al., 2010). These structural changes could facilitate a more efficient rise of water within the web.

Relative Changes in Capillarity

It's important to acknowledge that the reported percentage increases in capillarity (46.30% - 50.39% for scouring and 73.58% - 82.81% for mercerization) are relative values. They represent the improvement observed within each fibre orientation group (random, parallel, or cross-laid) when comparing treated webs (scoured or mercerized) to the corresponding unscoured webs.

While these relative changes provide valuable insights into the effectiveness of scouring and mercerization treatments on capillarity within each orientation group, they are not directly comparable across different fibre orientation categories. This limitation arises because the initial (unscoured) capillarity values for each orientation group likely differ. To fully understand the influence of fibre orientation on capillarity, a direct comparison of the absolute capillarity values (not percentage changes) measured for webs with random, parallel, and cross-laid fibre arrangements would be necessary.

Impact of Scouring, Mercerization, and Fibre Orientation on Capillarity

The observed percentage increases in capillarity due to scouring and mercerization (ranging from 46.30% to 82.81%) need to be interpreted with caution. These values represent relative improvements within each fibre orientation group (random, parallel, or cross-laid) compared to the corresponding unscoured webs. While these percentages highlight the effectiveness of the treatments, they are not directly comparable across different fibre orientation categories.

The seemingly high percentage increase for the cross-laid mercerized sample (73.97% - 92.49%) is likely a consequence of the initially lower capillarity observed for cross-laid webs (as previously established). Even with a substantial improvement, the absolute capillarity of the cross-laid mercerized webs might still be lower than that of randomly or parallel-laid webs after treatment.

This observation suggests that the influence of fibre orientation on capillarity might diminish as the fibres become progressively cleaner and their structure becomes more open due to the treatments. Scouring removes impurities that can hinder water interaction, while mercerization potentially disrupts the crystalline structure, creating a more accessible network for water movement within the fibres (Sadov et al., 1978; Ramesh et al., 2010). These combined effects might lessen the initial differences in capillarity caused by fibre orientation in the untreated webs.

Post-Dye Bath Capillary Rise

An interesting phenomenon was observed after removing the web samples from the dye bath. All sample types (unscoured, scoured, and mercerized) exhibited a continued rise in the dye level for a 15-minute period, mirroring the duration of their immersion in the dye bath. This sustained rise can be attributed to continued capillary action within the web structure.

The extent of this post-dye bath capillary rise varied depending on the fibre characteristics. Un-scoured webs displayed the smallest increase, ranging from 2% to 5%. This can be attributed to the presence of impurities and waxy substances on the fibre surface that can hinder capillary action (Sadov et al., 1978). Scouring, which removes these impurities, resulted in a more pronounced rise (10% to 18%). Mercerized webs exhibited the greatest post-dye bath capillary rise (22% to 30%). This can be explained by the potential changes induced by mercerization, such as increased surface area and a more open and accessible fibre structure, which could facilitate enhanced capillary movement of the dye solution (Ramesh et al., 2010).

The observed trend further reinforces the influence of fibre orientation on capillarity. The minimum capillary rise values were consistently observed in the cross-laid web samples, while the maximum values were found in the randomly oriented webs. Parallel-laid webs exhibited values between these two extremes. This aligns with the previously established relationship between fibre orientation and capillarity, where a more tortuous path in the random arrangement hinders vertical movement, leading to a higher rise.

Suitability of Cotton Varieties for Fabric Construction

The investigated cotton varieties exhibit favorable characteristics for a wide range of fabric constructions, with the exception of applications requiring very fine yarns or those demanding exceptionally long staple lengths (e.g., terry fabrics). This suitability stems from a combination of factors.

Firstly, these varieties demonstrate a high degree of maturity and possess relatively strong fibres. The reported tenacity values ranging from 9.10 to 10.17 g/tex significantly surpass the average of 4.0 – 5.0 g/tex. This superior strength translates to fabrics with enhanced durability and resistance to mechanical wear. Secondly, the color absorption potential of these cottons is promising. Given their favorable strength characteristics, these varieties could be strong contenders for applications where both high strength and good dyeability are crucial.

Potential in Sanitary and Paper Products

While the staple length might not be ideal for very fine fabrics, the study revealed an interesting finding for applications in sanitary and paper products. The observed trend of increasing water absorption with decreasing fibre length and fineness suggests that these cotton varieties could be suitable for such products, provided the staple length is further reduced to industry standards.

Furthermore, the study highlights the significant improvement in capillarity achieved through mercerization, particularly for randomly oriented fibres. This implies that a combination of mercerization, bleaching (optional), and random fibre orientation in short-staple cotton fibres could lead to the development of highly absorbent materials suitable for sanitary pads, wipes, napkins, tissue paper, tea bags, and similar applications.

Conclusion

This study explored how cotton fibre properties and treatments affect the water absorption of cotton webs. Several factors were identified as influential. Shorter, finer, and less mature fibres tended to absorb more water. Interestingly, there was an inverse relationship between fibre length, fineness, and strength with water absorption. In terms of fibre orientation, randomly arranged fibres displayed the highest capillarity, followed by parallel and then cross-laid structures. This likely relates to the differing water flow paths within the web. Scouring and mercerization treatments significantly improved both capillarity and water absorption. Scouring removes impurities that hinder water interaction, while mercerization potentially creates a more open and accessible fibre structure. While the studied cotton varieties had shorter staple lengths, their maturity, strength, and dyeability make them suitable for various fabric constructions. However, these properties also make them ideal for sanitary and paper products, particularly if the staple length is further reduced. Additionally, mercerization and random fibre orientation could be employed to further enhance their water absorption potential for these applications.

ACKNOWLEDGEMENT

The authors wish to acknowledge the contribution of the Institute for Agricultural Research (IAR) A.B.U. Zaria and Zazzau Ginnery for supplying the cotton samples. The Former also made available their Fibre Laboratory for Research while U.B.R, A.B.U; Zaria provided the research grant.

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