# Design and Development of a Gusset for a Leakproof Menstrual Underwear with Enhanced Absorption

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## I. Introduction

Reusable menstrual underwear is an undergarment designed to absorb and retain blood during the menstrual cycle. It is generally made with multiple layers of wicking and absorbing fabrics, including an additional barrier layer for leak-proofing [1]. An ideal menstrual underwear should possess adequate absorbency, mobility, leakage prevention, and environmental sustainability [2]. However, current commercially available products have the major limitations of limited absorbency despite their high bulkiness [3], insufficient gusset coverage, and limited durability [4].

The primary function of the skin-contact or wicking layer is to promptly wick the fluids into the subsequent absorbent layers [5]. Additionally, consumer reviews highlighted the need to minimize the spread of fluid and prevent rewetting of the skin contact surface [6]. The absorbent layer's role is to retain the menstrual fluid within the gusset, while the barrier layer prevents fluid leakage [7].

Despite existing research on menstrual underwear, a limited number of them focus on the design and development aspect [3]. Most studies and patents lack specific technical details of each layer but follow the common three-layer gusset layout consisting of wicking, absorbent, and barrier layers.

The wicking layer's requirements for one-way fluid transfer and maximum fluid spread in its outer surface can be achieved with fabrics that have less hydrophilic yarns, lower yarn counts, and higher filament counts on the skin-contact surface compared to the outer surface [8]. Weft-knitted spacer fabrics can satisfy this requirement, and they also possess the advantages of low bulk density, layered structure capability, good absorbent capacity, and design flexibility [9]. However, the use of spacer fabrics for enhanced wicking and absorbency in menstrual underwear has not been explored in published literature.

Electrospun nanofibrous mats have the potential to significantly improve absorbency levels while using sustainable and non-toxic raw materials such as Sodium alginate and Chitosan [10]. Thus, it could further enhance the absorbency of the gusset.

This study aims to address the major limitations of existing reusable menstrual underwear by designing and developing an effective gusset with enhanced absorbency, wicking, coverage, and leak-proofing. It also seeks to address the scarcity of published literature on reusable menstrual underwear design and development, focusing on Sodium alginate-based electrospun mats and spacer fabrics to enhance absorbency and wicking.

## II. Materials and Methods

### A. Wicking Layer Design and Development

Fifteen three-thread weft knitted spacer fabric structures were developed using a fully computerized 14-gauge flat knitting machine, and the machine parameters were kept constant for all structures. To achieve the requirements of one-way fluid transfer and maximum fluid spread on the outer surface, two sets of nylon (ContiFibre, Italy: Bright trilobal PA66, 40D/20f) and polyester (Toung Loong Textile MFG, Taiwan: Round hollow cross-section, 100D/100f) yarns were incorporated for the face and back yarns. A high moisture-wicking polyester Coolmax yarn (ContiFibre, Italy: Four channel cross-section, two-fold 78D/88f) was selected for the spacer yarn to promptly transfer the fluids to the back layer.

In all fifteen structures, face and back yarns formed only knit stitches. Seven of the structures (group A) had spacer yarn forming tuck stitches in the front bed and knit stitches in the back bed. The remaining eight structures (group B) had spacer yarn forming tuck stitches in both front and back beds. This selection was made to assess the effect of wicking by increasing the area of hydrophilic Coolmax yarn on the reverse side of the fabric through the knit stitches. Variations within the two groups were introduced by varying the number of consecutive knit, tuck, or miss stitches along a course or a wale.

### B. Absorbent Layer Design and Development

A two-layer composite fabric was selected for the absorbent layer. The first layer consisted of a sodium alginate-based electrospun nanofibrous mat, while one of the developed weft-knitted spacer fabrics from the fifteen structures was selected for the second layer to provide additional absorbency and support to the electrospun mat against distortion during washing.

To prepare the electrospun mats, a sodium alginate 1% (w/v) solution was first prepared by dissolving sodium alginate in distilled water and stirring it with a magnetic stirrer for 6 hours at 50°C. Then, five PVA solutions with concentrations of 9%, 12%, 20%, 25%, and 30% were prepared by dissolving PVA powder in distilled water by stirring with a mechanical stirrer for 6 hours at 80°C and maturing at room temperature for 12 hours. Next, these solutions were mixed with the volume ratios of 1:2, 1:5, 1:2, 1:2, and 1:2, stirring with the mechanical stirrer for 3 hours at room temperature. The solutions were kept at room temperature for 24 hours before electrospinning. For the final solution, 1% Triton X-100 (w/v) was also added to the NaAlg solutions before mixing with the PVA solution to enhance fiber formation [11].

The prepared electrospinning solutions were sonicated for 10 min before electrospinning to ensure homogeneity [10]. Nanofiber mats with uniform thickness were produced using a conventional electrospinning setup with the parameters of 20 kV voltage, 0.6 mm spinneret diameter, 15 cm tip-to-collector distance, and 0.01 ml/min flow rate, which were identified through the initial trials. Then, the fiber mats were immersed in an acetone solution with 0.15 M 50% glutaraldehyde and 0.05M 37% HCl acid for 24 hours at room temperature for cross-linking. Next, the mats were immersed in 99.5% ethanol for 5 minutes for neutralization. Finally, the mats were washed three times with 1% phosphate tampon solution and oven-dried at 50°C for one hour.

### C. Barrier Layer, Gusset Shape, Layout, and Construction

A 100% polyester interlock knitted fabric with a waterproof and breathable Polyurethane lamination was selected and sourced for the barrier layer.

The gusset was designed with a tapered front and wide back, following the natural contour of the human body as illustrated in Fig. 1. Based on the test results, the best-performing fabrics and materials were selected for each layer of the gusset. For layer assembly, the wicking layer, two absorbent layers, and the barrier layer were stacked in sequence as illustrated in Fig.2. An additional allowance on the barrier layer was folded over the edge to enclose the stacked layers to prevent leakage through the edges. The combined gusset is to be laid on top of the body fabric to attach it to the underwear. Finally, the layers were combined using adhesive bonding technology.

### D. Testing and Evaluation

#### 1) Spacer Fabric Developments

The fifteen developed fabric structures were tested using the Moisture Management Test (MMT: AATCC 195), Fabric Weight Test (GSM: ASTM D3776), and Fabric Thickness Test (ASTM D1777-96).

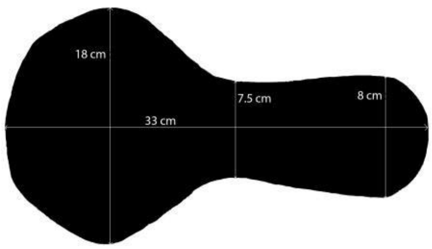


Fig. 1. Gusset shape and dimensions (For a medium sized underwear)

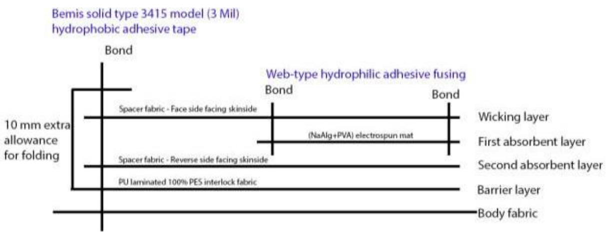


Fig. 2. Gusset construction

For the moisture management test, values for wetting time, absorption rate, maximum wetted radius, accumulative one-way transport index, spreading speed, and overall moisture management capacity (OMMC) were obtained for each side of the fabric structures. In this test, the side of the specimen onto which the liquid is dropped is referred to as the top surface. Based on the test results, the best four fabric structures were selected. To validate their effectiveness for menstrual underwear applications, the selected fabrics were compared with a commercially available high-wicking fabric. The reference fabric had a mesh jersey structure along with a zonal-wicking finish and a GSM of 140.

The best four spacer structures were tested for absorbent capacity with a modified version of the FEMTECHMAS-6513-1:2023 standard. A commercially available, high-absorbency, 100% polyester fleece terry fabric with a brushed surface was used for comparison (370 GSM, 2.1 mm thickness). Based on both wicking and absorbency performance, the best-performing spacer structure was selected to be used in wicking, and the second absorbent layers.

#### 2) Electrospun Nanofibrous Mats

The solution combination that showed the least amount of beading and unevenness during electrospinning was chosen. If multiple combinations met this criterion, the combination with the highest sodium alginate concentration was selected as it leads to better fluid absorbency [10]. The wet pickup of a specimen of the developed electrospun mat was also measured to evaluate its raw absorbent capacity.

For further analysis, three circular-shaped mini-gusset specimens were developed. The first two specimens followed a similar layout to the two full-size gusset specimens, while the third was a reference specimen created using the reference wicking fabric and the reference absorbent fabric used for test result comparison. The second specimen's electrospun mat had the dimensions of 1 cm by 0.6 cm. These specimens were tested with the modified version of the FEMTECHMAS-6513-1:2023 standard for three wash cycles to evaluate their durability.

#### 3) Gusset Specimens

Two full-size gusset specimens were developed following the layout described in section II.C. One specimen was composed of two spacer fabrics and the barrier layer while the other incorporated all four layers, including the electrospun mat, which had the dimensions of 4 cm by 2.8 cm. The specimens were tested according to the FEMTECHMAS-6513-1:2023 standard for Maximum Absorbent Capacity Before Leakage, Garment Rewet Volume, and Wicking Speed, using a synthetic blood stimulant. The testing was conducted through Bureau Veritas Consumer Products Services Lanka (Pvt) Ltd.

## III. RESULTS AND DISCUSSION

### A. Spacer Fabrics

All fifteen structures showed positive values greater than 100 for the one-way-transport capacity indices of face side to reverse side, which were also significantly higher than their indices for reverse side to face side. Thus, it can be concluded that the designed spacer structures successfully met the one-way-transport requirement. Group B significantly outperformed Group A, with a mean one-way-transport capacity index of 298.622 compared to Group A's mean value of 214.077. For the max wetted radii ratio between the two faces, group A underperformed, with all its structures showing a value of 1.0. Meanwhile, group B showed a mean value of 1.52, with all structures having a value greater than 1.0. Therefore, only group B met the identified fluid spread requirement. Among the fifteen structures, structure B2 performed the best with a one-way-transport capacity index of 468.8149, a maximum wetted radii ratio of 2.40, and a thickness of 1.2 mm, even outperforming the reference wicking fabric that showed values of 398.5747 and 1.5 respectively. It also showed the highest absorbency, with a value of 20 ml per 100.4 cm² area (modified FEMTECHMAS-6513-1:2023 standard). Notably, it showed a 4 ml higher absorbency than the terry fabric with a significantly lower thickness and GSM. Therefore, B2 was selected to be used for wicking and absorbent fabric layers. The test results of the top four spacer structures along with the reference terry fabric, are presented in Table 1.

### B. Electrospun Mats

During the electrospinning trials, it was observed that the solution with 12% PVA concentration and 1:5 NaAlg: PVA ratio was the optimal combination for achieving smooth fiber formation without beading. The processed mats showed a low thickness range of 0.1 to 0.3 mm and a semi-brittle, gel-like texture. A 2.8 cm by 2 cm rectangular specimen showed a wet pickup of 130.08%, indicating its effectiveness.

### C. Gusset Specimens

For the circular gusset specimens, the gusset with the electrospun mat (thickness 1.73 mm, weight 6.59 g) showed an absorbency value of 20 ml, whereas the specimen without the electrospun layer (thickness 1.65 mm, weight 5.86 g) showed a value of 18 ml. Notably, the reference specimen (2.63 mm, weight 7.50 g) only showed a value of 8 ml despite its higher weight and thickness. All specimens maintained their absorbency values throughout all three wash cycles, indicating their durability against washing. The reduction of absorbency level compared to the fabric form can be attributed to the decrease of the gusset thickness caused by the flat-press operation during bonding.

For the full-sized gusset specimens tested with FEMTECHMAS-6513-1:2023 standard, the specimen without the electrospun layer showed an absorbency volume of 39 ml, a wicking time of 10 s, and a rewet of 28.3%. In contrast, the gusset incorporating the electrospun mat showed a remarkable absorbency level of 51 ml, with a wicking time of 12 s and a rewet of 24.3%. Notably, an increase of 12 ml was achieved with a small rectangular electrospun specimen measuring only 4 cm by 2.8 cm. Furthermore, even the gusset without the electrospun mat showed a high absorbency level of 39 ml and a low wicking time. These results validate the effectiveness of the proposed spacer structures and the electrospun fiber mat for enhanced wicking and absorbency in menstrual underwear.

TABLE I. BEST PERFORMING SPACER STRUCTURES

| Structure | GSM | One-Way-Transport Capacity | Max Wetted Radii Ratio | Absorbent Capacity (ml) |
|---|---|---|---|---|
| B2 | 176 | 468.8149 | 2.40 | 20 |
| B4 | 233 | 388.4187 | 1.67 | 18 |
| B8 | 180 | 335.7741 | 1.67 | 12 |
| B5 | 244 | 331.4806 | 1.33 | 16 |
| Terry | 370 | Not tested | Not tested | 16 |

## IV. CONCLUSION

The developed best-performing spacer structure achieved a one-way-transport capacity index of 468.82 and a maximum wetted radii ratio of 2.40, surpassing the reference fabric by 17.63% and 60% respectively. It also demonstrated an absorbent capacity of 20 ml, surpassing the bulkier reference terry fabric by 4 ml. The designed gusset achieved an impressive absorbency of 51 ml, with a prompt wicking time of 12 s, and a low rewet of 24%. The incorporation of the electrospun membrane enhanced the absorbency by 30.77% while reducing the rewet by 14.13%. Durability was confirmed through three wash cycles using mini-gusset specimens. Thus, the developed prototype effectively addressed the limitations of reusable menstrual underwear by enhancing wicking, absorbency, and leak-proofing. Additionally, this study bridges a critical gap in the literature by providing detailed technical insights into menstrual underwear design, paving the way for future innovations in this domain.

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